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GLOBAL ANALYSIS OF THE POTENTIAL FOR N_2O PRODUCTION IN NATURAL SOILS

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Abstract. A simple global model of the production potential of nitrous oxide (N_2O) in natural soils is developed to analyze the relative importance, both geographically and seasonally, of the different controls on N_2O production at the global scale. Five major controls on N_2O production are included: (1) input of organic matter, (2) soil fertility, (3) soil moisture status, (4) temperature, and (5) soil oxygen status. Indices for the controls are derived from global gridded (1°×1° resolution) data bases of soil type, soil texture, NDVI and climate. The model explains close to 60% of the variability found in measurements reported at about 30 sites in six different ecosystems throughout the world. Although this result is reasonable for global analyses, the correlation is considered insufficient to make global estimates of nitrous oxide emission with confidence. The model confirms conclusions from earlier studies that the major source regions of nitrous oxide are in the tropics.

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1. INTRODUCTION

Nitrous oxide (N_2O) is present in the atmosphere in trace quantities. Its concentration in 1990 was about 310 parts per billion by volume (ppbv), about 1000 times less than that of CO_2, and it is increasing at the rate of about 0.8 ppbv y^{-1} [Watson et al., 1992]. The seemingly small growth rate, about 0.25% y^{-1}, is the result of a large imbalance (about 30%) between the sources and sinks [Prinn et al., 1990; Khalil and Rasmussen, 1992]. Despite its low abundance in the atmosphere, N_2O plays an important role. Its long lifetime of ~132 years [Isaksen et al., 1992] means the system has a long memory of its emission history. The radiative forcing of N_2O is, molecule for molecule, about 200 times that of CO_2 [Isaksen et al., 1992]. In the stratosphere the principal mechanism for N_2O destruction is by photolysis; in addition, N_2O is destroyed by reaction with excited oxygen atoms [Crutzen, 1976]. The latter reaction is the largest source of stratospheric NO (nitric oxide), initiating a complex set of gas phase reactions that lead to catalytic ozone destruction.

Neither the sources nor the causes for the increase in N_2O are well known. It is generally accepted that the most important source is natural soils, seconded by emissions from the oceans [Seiler and Conrad, 1987] although there is significant uncertainty regarding the distribution and magnitude of the sources themselves. For some time it was thought

that, like CO_2, the primary cause for the increasing concentration was combustion of fossil fuels, in particular, coalburning power plants producing electricity [Hao et al., 1987]. However, identification of an artifact in the flask sampling procedure ruled out combustion (including biomass burning) as the major cause of the trend [Muzio and Kramlich, 1988]. Minor sources identified so far include agricultural fields amended with nitrogenous fertilizers, animal manure, aquifers, sewage, industry, automobiles, biomass burning, land clearing, and trash incineration [Watson et al., 1992; Khalil and Rasmussen, 1992]. It is not clear if these sources can account for the secular trend.

In soils and aquatic systems, microbial processes are responsible for both the production and consumption of atmospheric nitrous oxide and nitric oxide. In vitro experiments demonstrate significant N_2O production by both denitrifiers [Firestone et al., 1980] and nitrifiers [Yoshida and Alexander, 1970; Blackmer et al., 1980; Lipschultz et al., 1981; Poth and Focht, 1985]. Recently, it was observed that N_2O may also be formed by other processes [Robertson and Tiedje, 1987; Tiedje, 1988], but the significance of these processes on a global scale, and their mechanisms and regulators, are poorly known.

Denitrification comprises the group of processes whereby nitrogenous oxides, principally nitrate (NO_3^-) and nitrite (NO_2^-), are reduced to dinitrogen gases (N_2), nitrous oxide and nitric oxide [Firestone and Davidson, 1989]. It occurs under oxygen-limited conditions; under strictly anaerobic conditions, nitrous oxide and nitric oxide may also serve as electron acceptors. Several processes, including abiotic ones, all match this definition [Firestone and Davidson, 1989]. Under natural conditions, the nitrate available for denitrification depends on the rate of nitrification [Myrold and Tiedje, 1985; Tiedje, 1988]. With relatively high nitrate supply, denitrification is related primarily to the amount of available organic compounds [Ottow et al., 1985] and N_2O production shows a strong positive correlation with both CO_2 evolution and available carbon [Eaton and Patriquin, 1989].

In nitrification, ammonia (NH_4^+) is oxidized to nitrite (NO_2^-) or nitrate (NO_3^-). In natural soil ecosystems, the ammonia comes mainly from decomposition and mineralization of organic matter. Nitrogen inputs to natural ecosystems come from N deposition and biological dinitrogen fixation [Boring et al., 1988]. Major regulators of nitrification are temperature, oxygen, nutrient availability, carbon and nitrifiable N sources. Under oxygen-limited conditions, nitrifiers can use NO_2^- as a terminal electron acceptor to avoid accumulation of the toxic NO_2^-, whereby N_2O is produced [Poth and Focht, 1985]. While denitrification is inhibited by oxygen, nitrification is an aerobic process. Therefore denitrification in constantly anaerobic systems is low since under such conditions, nitrification is blocked by lack of oxygen [Sahrawat and Keeney, 1986; Bowden, 1986].

There is considerable controversy about the relative importance of nitrification and denitrification for N_2O production. Many researchers have suggested that nitrification is the major source of N_2O in "aerobic" agricultural soils [Ryden et al., 1978; Breitenbeck et al., 1980; Bremner and Blackmer, 1981; Klemedtsson et al., 1988] and in natural semiarid "well aerated" soils [Anderson et al., 1988; Parton et al., 1988]. In peat sediments [Gordon et al., 1986], certain tropical forests [Livingston et al., 1988; Keller et al., 1988; Robertson and Tiedje, 1988] and some temperate forests [Eaton and Patriquin, 1989], denitrification may be the major process involved. Apparently, nitrification is a relatively constant process across ecosystems while denitrification rates are temporally and spatially variable [Firestone and Davidson, 1989].

Estimates of the annual N_2O release from natural soils illustrate the uncertainty about this source. The ranges are 7-16 Tg (Tg = 10^{12}g) [Bowden, 1986], 3-25 Tg [Banin, 1986], 39 Tg [Seiler and Conrad, 1987], and 2.8-7.7 Tg [Watson et al., 1992]. Most of these studies rely on one or a few flux measurements, multiplied by areas of broad vegetation groups, to derive global emissions. These "representative measurement" approaches cannot explain the extreme variability of fluxes observed both in space and time. Fluxes of N_2O from temperate grasslands have been modeled extensively [e.g., Parton et al., 1988]; a model based on rainfall events and detailed description of microbiological and physical soil processes was developed by Li et al. [1992]. While conceptual models of nitrification and denitrification exist [e.g., Robertson, 1989; Firestone and Davidson, 1989; Davidson, 1991], extrapolation from site-specific measurements or models to regional or global emissions is a considerable challenge. Schimel et al. [1988] and Matson et al. [1989] stressed the need for stratification of ecosystems to describe the variability of environmental conditions responsible for N_2O fluxes: Matson and Vitousek [1990] stratified tropical forests primarily on the basis of soil fertility. Such approaches lead to better-justified regional estimates of N_2O emissions.

The global scale of the modeling presented here makes description of soil processes a difficult task. It is necessary to identify the major controls, and to describe and quantify their relative importance in a simple way. Our working hypothesis is that, since N_2O can be produced by both nitrifiers and denitrifiers, the potential for N_2O production in upland soils under natural conditions is related to the amount of nitrogen cycling through the soil-plant-microbial biomass system [Matson and Vitousek, 1987; Firestone and Davidson, 1989], hence to the N mineralization, nitrification, and denitrification rates

[Matson and Vitousek, 1987; Robertson and Tiedje, 1984; Martikainen, 1985]. In this "process pipe" or "hole in the pipe" concept [Firestone and Davidson, 1989; Davidson, 1991] the size of the holes or leaks in the pipe through which N_2O and NO escape is determined by factors that control the partitioning of the reacting N species to N_2O or more reduced/oxidized products. The rate at which N moves through the process pipe determines the importance of the leaks. This means that low denitrification rates lead to low trace gas release, regardless of the relative proportions of end products [Firestone and Davidson, 1989; Davidson, 1991].

We present a simple global model to analyze the geographic and seasonal variations of the various controls of N_2O production and their relative importance in the total annual emission. The focus is natural ecosystems, the largest single source term in the present-day N_2O budget. Given the paucity of available flux measurements, an immediate goal is to test the simple model of N_2O fluxes and to identify gaps where measurements and analyses are needed to reduce uncertainties about this source term.

The major controls on N_2O emissions in the model are discussed in section 2. The synthesis of these regulators into a simple schematic model for determining the N_2O emission potential is described in section 3. The one-dimensional model is applied at every 1°×1° gridbox globally. Modeled distribution of N_2O production potential and its sensitivity to the controlling factors are presented in sections 4.1 to 4.3. Regression relationships between modeled and observed N_2O emission values are presented in section 4.4, yielding an equation to translate the modeled non-dimensional N_2O potentials into dimensional fluxes (section 4.5). Global data sets of surface climate, soil properties, and satellite observations of the normalized difference vegetation index (NDVI), used to derive the geographic variation of the controls used in the model, are discussed in the appendix.

2. MAJOR CONTROLLING FACTORS OF N_2O PRODUCTION IN SOILS

The global model of N_2O production potential is based on the hypothesis that N_2O fluxes are directly related to the rate of nitrogen cycling through the soil-plant-microbial system. Hence we need to describe general patterns of decomposition and N mineralization, and, given the amount of N available in the soil, the major determinants of nitrification and denitrification.

Climate, vegetation, and soil are fundamentally interrelated to determine the ecosystem that develops in a particular area. The parent rock and soil type determine the type of vegetation via nutrient availability. Sites with low nutrient availability select for species with low nutrient demands producing low-quality litter which decomposes slowly and further reduces nutrient availability [Anderson, 1992]. Soil properties are also molded by the vegetation, particularly the amount and nature of organic matter formed during decomposition of plant detritus. Soils can have low fertility for various reasons. Low pH causes low solubility of a number of major and minor trace elements while the solubility of other elements (e.g., aluminum) increases. Highly weathered soils of the tropics (e.g., Ferralsols and Acrisols) usually contain less phosphorous than younger, less weathered soils of the temperate regions; they may even show P-fixation [Jordan, 1985; Duxbury et al., 1989; Driessen and Dudal, 1991].

Decomposition rates [Jordan, 1985] and mineralization processes are closely related to soil fertility because of feedbacks between litter quality, decomposition rates and nutrient availability [Adams et al., 1970; Zimka and Stachurski, 1976; Miller, 1981; Vitousek, 1982]. In general, concentrations of all major nutrients, including nitrogen, in aboveground and belowground forest biomass are markedly higher in fertile soils than in poor ones [Vitousek and Sanford, 1986].

Decomposition and mineralization rates are determined also by litter properties, most notably lignin concentration and C/N ratios. With low lignin concentrations (~10-15%) decomposition rates can be predicted from nitrogen concentrations or C/N ratios, while with high lignin concentrations the lignin/N ratio or initial lignin determines decomposition [Anderson, 1992]. The C/N ratio of organic material supplied to the soil influences the amount of N immobilized in microbial biomass. This influences N availability which in turn may affect nitrification and denitrification activities and products of denitrification [see Ottow, 1985]. The low C/N ratio in tropical forests leads to rapid and more complete decomposition of organic matter inputs [Duxbury et al., 1989] and high N mineralization rates in these soils [Vitousek and Sanford, 1986].

Soil moisture and temperature control soil processes at all levels and are important factors governing the speed of organic matter decomposition. Because of year-round high temperatures, soil processes in the humid tropics can remain active throughout the year, and annual nutrient cycling can be faster than in regions where cold or drought interrupts these processes. Jenkinson and Ayanaba [1977] estimated that decomposition rates in the tropics are four times those in temperate zones, while decomposition in mediterranean regions has been found to be twice that in temperate climates [Oades, 1988]. Measurements of soil organic matter stocks and leaf litterfall suggest that decomposition rates mimic global patterns of temperature and moisture. Post et al. [1985] noted that the C/N ratio is generally lower

in warm climates. This is consistent with the observation that tropical forests generally cycle 2-4 times more nitrogen between soil and vegetation than do most temperate ecosystems [Vitousek, 1984; Jordan, 1985]. However, this may be caused by ecosystem characteristics other than temperature. Apparently, nitrogen is not limiting growth in these tropical systems but other nutrients, such as phosphorous in strongly leached soils, may be limiting [Vitousek, 1984]. Because of nitrogen limitation, temperate forests generally have higher C/N ratios in litter and slower N mineralization rates than do tropical forests [Robertson and Tiedje, 1984; Jordan, 1985; Vitousek and Sanford, 1986; Vitousek and Matson, 1988]. Fluxes in temperate forests are much lower than those in most tropical environments, which may be explained by lower N availability and less favorable moisture and temperature conditions.

Soil-water content is the balance of inputs from rainfall, leaching and capillary rise, and consumption by plants. It has been shown to influence N_2O emissions from well-drained soils [Mosier and Parton, 1985; Klemedtsson et al., 1988; Groffman and Tiedje, 1988]. Aerobic microbial activity increases with soil-water content until water displaces air and restricts oxygen diffusion so that maximum rates of microbial respiration, nitrification and mineralization occur at the highest water content at which soil aeration remains nonlimiting. This critical water content is strongly dependent on soil texture. In general, microbial activity peaks at 60-80% of field capacity [Linn and Doran, 1984], the amount of water held at soil-water potentials of about 10 kPa (10 kPa = 0.1 bars). Nitrification and associated N_2O production also show maximum activity at 60-80% of field capacity [Greaves and Carter, 1920; Davidson, 1991].

Optimum conditions for denitrification may occur at water contents from 80% to over 100% of field capacity [Linn and Doran, 1984; Klemedtsson et al., 1988]. There is, however, a clear hysteretic effect whereby respiration and denitrification rates slowly decrease monotonically during the drying phase [Groffman and Tiedje, 1988]. Soils close to saturation show low N_2O production [Davidson, 1991] because N_2O diffusion may be limited [Sahrawat and Keeney, 1986; Keller et al., 1986] resulting in a greater fraction of N_2O reduced to N_2. Uptake of N_2O from the atmosphere by wet soils may occur under very wet conditions [Ryden, 1981, 1983; Letey et al., 1981; Smith et al., 1983; Keller et al., 1986].

Wetting of dry soils causes pulses in N mineralization, nitrification and N_2O fluxes [Denmead et al., 1979; Letey et al., 1981; Mulvaney and Kurtz, 1984; Sextone et al., 1985; Mosier et al., 1981, 1986; Parton et al., 1988; Vitousek et al., 1990]. Letey et al. [1981] showed that release of N_2O from the soil to the atmosphere is enhanced by alternate drying and wetting of soils although peaks in N_2O production may decline with subsequent wetting events.

Overall denitrification activity is strongly stimulated at low oxygen pressures [Colbourn and Harper, 1987; Firestone and Davidson, 1989] but associated N_2O fluxes are low under anaerobic conditions [e.g., Terry et al., 1981; Davidson, 1991]. Oxygen status of soils is controlled by the interplay between water inputs, oxygen supply, and oxygen consumption. Soil-water content is crucial as oxygen diffuses 10^4 slower in water than in air [Nye and Tinker, 1977].

Soil oxygen is consumed by root respiration and microbial activity. Oxygen consumption by microorganisms is driven by the supply of carbon and, under dry conditions, by water as a stimulator of metabolic activity. Denitrification is often found in "hot spots" created by decomposing organic matter which generates anaerobic microsites [Dowdell and Smith, 1974; Duxbury et al., 1982; Parkin, 1987; Schmidt et al., 1988]. This phenomenon may explain some of the high spatial variability of soil denitrification commonly observed [Ryden et al., 1978; Rolston et al., 1978; Breitenbeck et al., 1980; Bremner et al., 1980; Mosier et al., 1981; Folorunso and Rolston, 1984; Colbourn et al., 1984; Goodroad and Keeney, 1985; Colbourn and Harper, 1987].

A strong relationship exists between soil texture and denitrification activity [Groffman and Tiedje, 1989]. Fine-textured soils have more capillary pores within aggregates than do sandy soils, thereby holding soil water more tightly. As a result, anaerobic conditions may be more easily reached and maintained for longer periods within aggregates in fine-textured soils than in coarse-textured soils. Soil-drainage characteristics also influence denitrification activity [Colbourn and Harper, 1987; Groffman and Tiedje, 1989] by affecting soil aeration.

Studies on the effect of temperature on N_2O fluxes show Q_{10} values of 5 at 10°C to 1.5 at 30°C [Mosier and Parton, 1985], 2.8 between 15° and 25°C [Denmead et al., 1979], 2.28 between 10° and 20°C, 1.99 from 20° to 30°C and 1.35 at 30° to 40°C [Blackmer et al., 1982]. Temperature may not control the release of N_2O in ecosystems where soil nitrogen temporarily accumulates due to wet-dry cycles or freeze-thaw cycles [Anderson and Poth, 1989]. Denitrification during early spring and autumn in temperate climates may account for a significant portion of the annual N_2O released [Keeney et al., 1979; Goodroad and Keeney, 1984a; Schmidt et al., 1988; Christensen and Tiedje, 1990].

Soil pH also has a marked effect on the products of denitrification. Denitrification rates are low under acid conditions and more rapid under slightly alkaline conditions, but the N_2O fraction may be larger at low soil pH [Focht, 1974; Goodroad and Keeney, 1984b; Martikainen, 1985; Eaton and Patriquin, 1989; Brumme and Beese, 1992],

particularly with an adequate nitrate supply. This is commonly attributed to the sensitivity of N_2O reductase to proton activity [Alexander, 1977]. Simply lowering soil pH does not always increase the N_2O ratio suggesting that the soil and its resident organisms, rather than pH per se, determine the N_2O fraction [Ottow et al., 1985]. This may be due to the observed apparent adaptation of strains of denitrifiers to low pH [Parkin et al., 1985].

3. MODEL DESCRIPTION

The following parameters were selected as control variables in the N_2O model: (1) input of organic matter (CARBON); (2) soil fertility (FERT); (3) temperature effect on organic matter decomposition and nitrogen mineralization (SOD); (4) soil-water availability affecting decomposition, mineralization and nitrification (H2O); and (5) soil-oxygen limitation affecting denitrification (O2).

We assume that organic matter input is proportional to litter amount which in turn is proportional to net primary productivity of the vegetation. The mobilization rate of nitrogen in organic matter is proportional to the rate of decomposition and mineralization as determined by soil temperature, soil moisture and soil fertility. We recognize that composition of the organic material is also an important determinant of decomposition rate. However, there is no global dataset or proxy dataset for lignin content or C/N ratios in litter, and so we have not included these controls explicitly. As C/N ratio may be related to temperature [Post et al., 1985] and soil fertility [Vitousek and Sanford, 1986], their effect on decomposition and mineralization rates may be indirectly captured by temperature (SOD) and fertility (FERT) factors.

Soil pH has also been identified as a regulator for N_2O production. Because global data on soil pH is lacking, this soil property is not included as a separate factor in this study. Instead, we assume that soil pH and soil fertility are closely related and hence complementary.

A central part of the model is a description of soil-water regulation of nitrification/denitrification. We use a bucket model of water balance, which includes variations in soil drainage and topsoil texture and determines monthly water status of the topsoil. If the soil-water status is high, there is high water availability and low oxygen availability - conditions favorable for denitrification. The model is described below and illustrated schematically in Figure 1. Three of the five regulators vary monthly: SOD, H2O and O2. The remaining two, FERT and CARBON, are constant through the year.

Because of the lack of quantitative relationships between N_2O fluxes and the various controlling parameters for soil types on a global scale, our strategy was to first translate ideas about relative importance into ranked nondimensional indices. The indices range from 0 to 10 or from 1 to 5, with high numbers signifying importance for N_2O production. Such translations may be straightforward for numeric data such as temperature. For control factors such as soil fertility, a subjective ranking of soil units was carried out. The suite of control indices were then combined to form indices for N_2O fluxes.

The focus of the model requires data which are global in domain and which span at least a year. The finest spatial resolution of the primary data sets used is 1° latitude by 1° longitude, about 110 km × 110 km at the equator. For these reasons, the model cannot resolve episodic effluxes of N_2O after rainstorms, localized "hot spots" and high spring and autumn emissions in temperate ecosystems which are often reported. The importance of such high-frequency, local events in the global budget has not been established.

The primary gridded data bases on climate, soil type, soil texture, and vegetation are discussed in the appendix. The global distribution of soil groups is shown in Plate 1.

Input of organic matter (CARBON). Under natural conditions, litterfall and root decay are the major sources of carbon and nitrogen to the soil. Most ecosystems have abundant surface litter throughout the year. Therefore the seasonal variation of C and N mobilization in the litter is governed more by decomposition rates rather than by seasonal variations in litterfall. We assume that the geographic pattern of annual litterfall is the same as that of annual net primary productivity (NPP). NPP is the result of soil and environmental conditions, and for many temperate ecosystems also the result of nitrogen availability. Hence NPP may only be correlated indirectly to nitrogen.

The satellite-derived normalized difference vegetation index (NDVI; see appendix) has been shown to be a good correlate for NPP [Goward et al., 1986; Box et al., 1989]. The annual integral of the NDVI, rather than monthly NDVI values, is used because litterfall is asynchronous with productivity and with nitrogen mineralization and nitrogen may be immobilized in microbial biomass before it is liberated.

Monthly NDVI composites for 1984 are gridded at 1° resolution for the globe, and summed to produce the annual integral. Monthly NDVI values range from -0.1 to 0.5, and annual totals range from -0.1 to 4.0. For consistency with other factors used in the study, the NDVI totals are rescaled to range from 0 to 10, for the index CARBON (Plate 2). Use of the NDVI captures the variability of NPP at the same resolution as that of the soil data.

Soil fertility (FERT). In this study, soil fertility is the inherent capability of soil material to supply nutrients to plant roots [see Sanchez, 1976; Brady, 1976]. This definition excludes soil N availability which is a combined result of vegetation, climate,

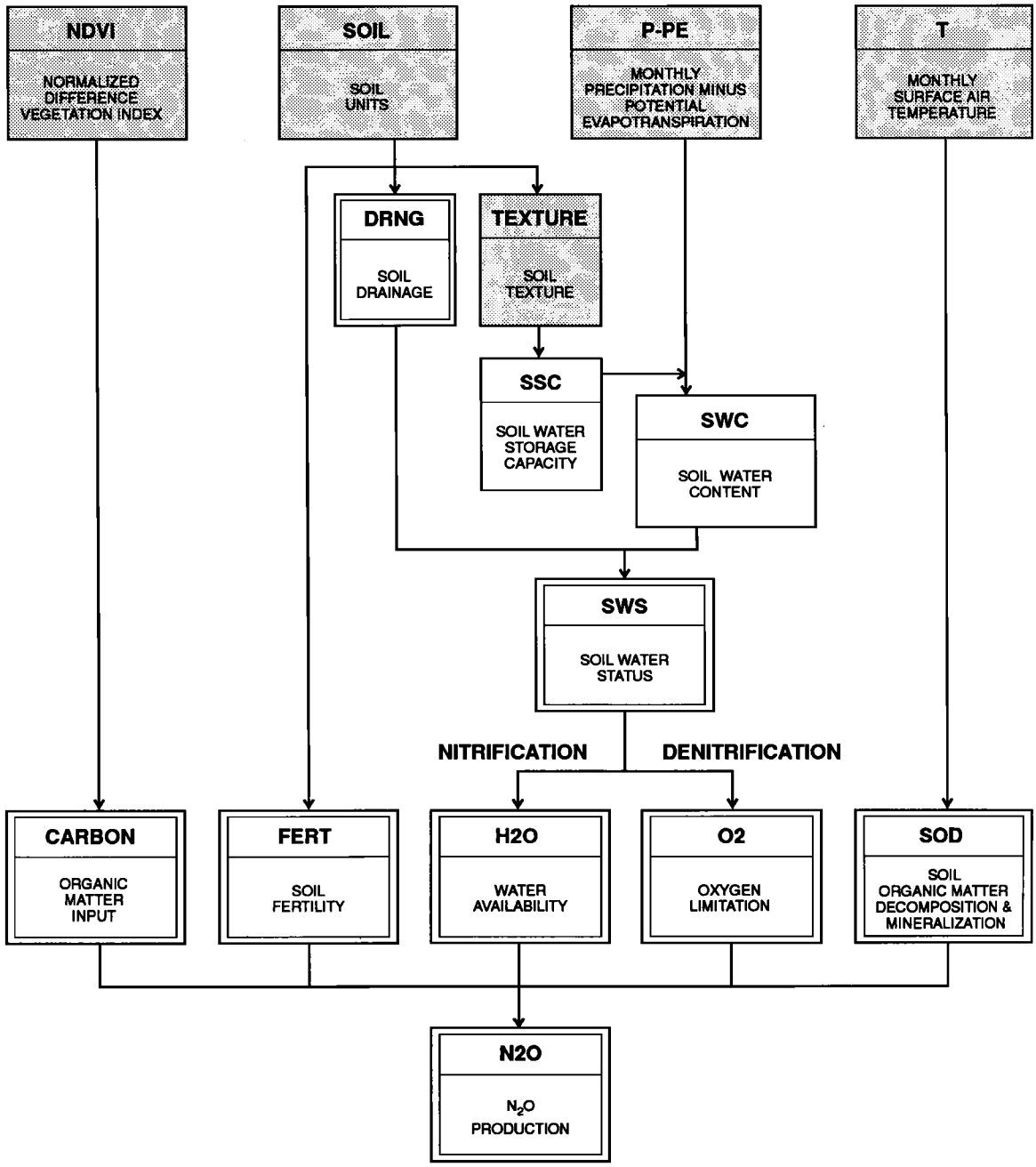

Fig. 1. Schematic diagram of the model of N_2O production. Shaded boxes denote input data and double-bordered boxes denote nondimensional indices.

and soil. With this definition, mineralization of nitrogen is indirectly determined by the combination of CARBON, FERT, SOD and H2O.

Soil characteristics important for inherent fertility are soil pH, cation exchange capacity, base saturation, and amounts of weatherable minerals; in some cases P fixation also plays a role. The scale for soil fertility is adapted from Food and Agriculture Organization (FAO) [1981] for the major FAO/Unesco soil groups (Table 1); indices for some individual soil units within groups vary due to their diagnostic horizons or properties. For example, Nitosols (Table 1, soil group 12) are highly fertile soils common to the tropics. Within the group of Nitosols, the dystric Nitosols are assigned a lower index because their base saturation is less than 49%

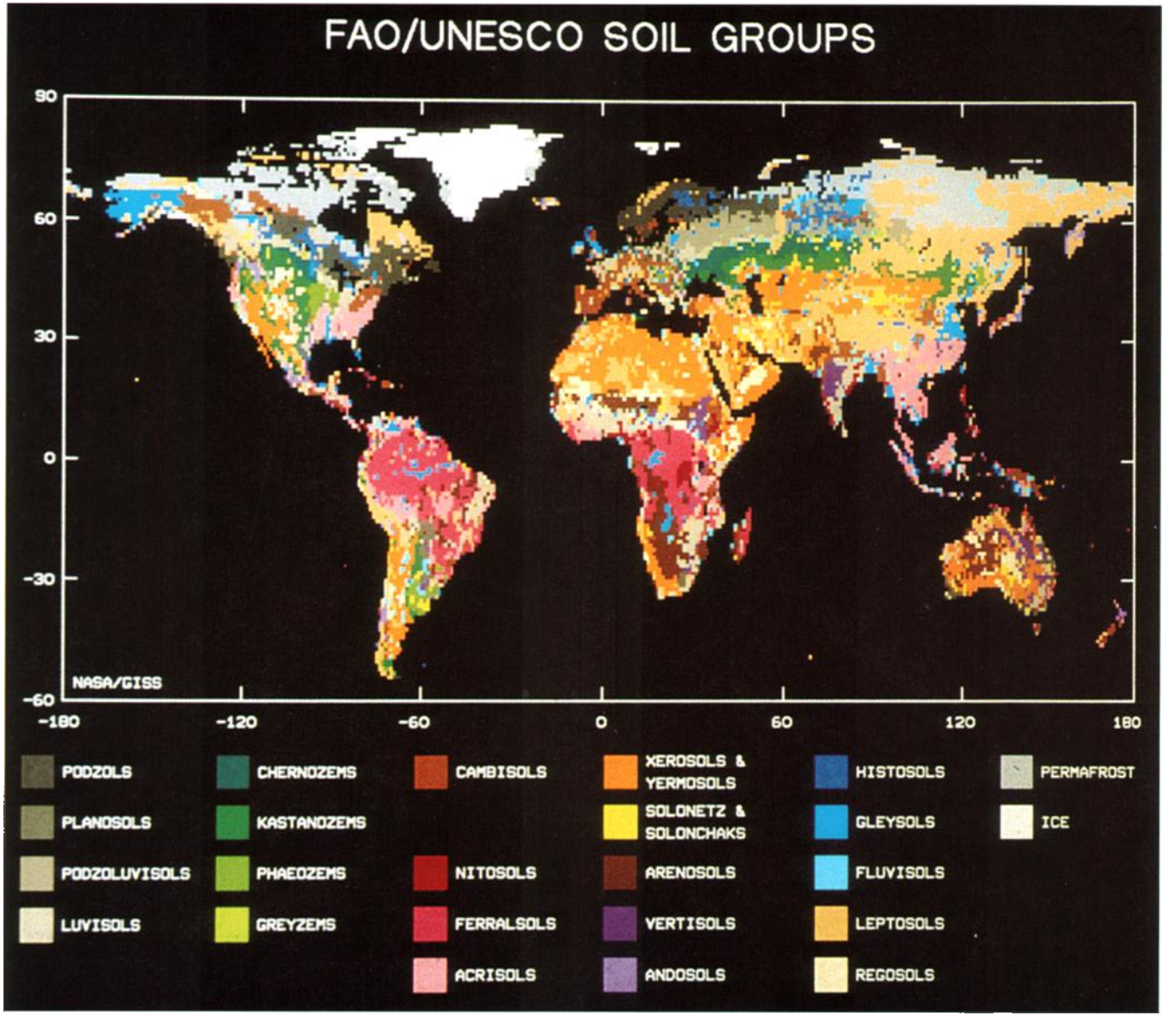

Plate 1. Distribution of major soil groups from the data set of Zobler [1986] digitized from FAO [1974-1981] soil maps. See Table 1 for descriptions.

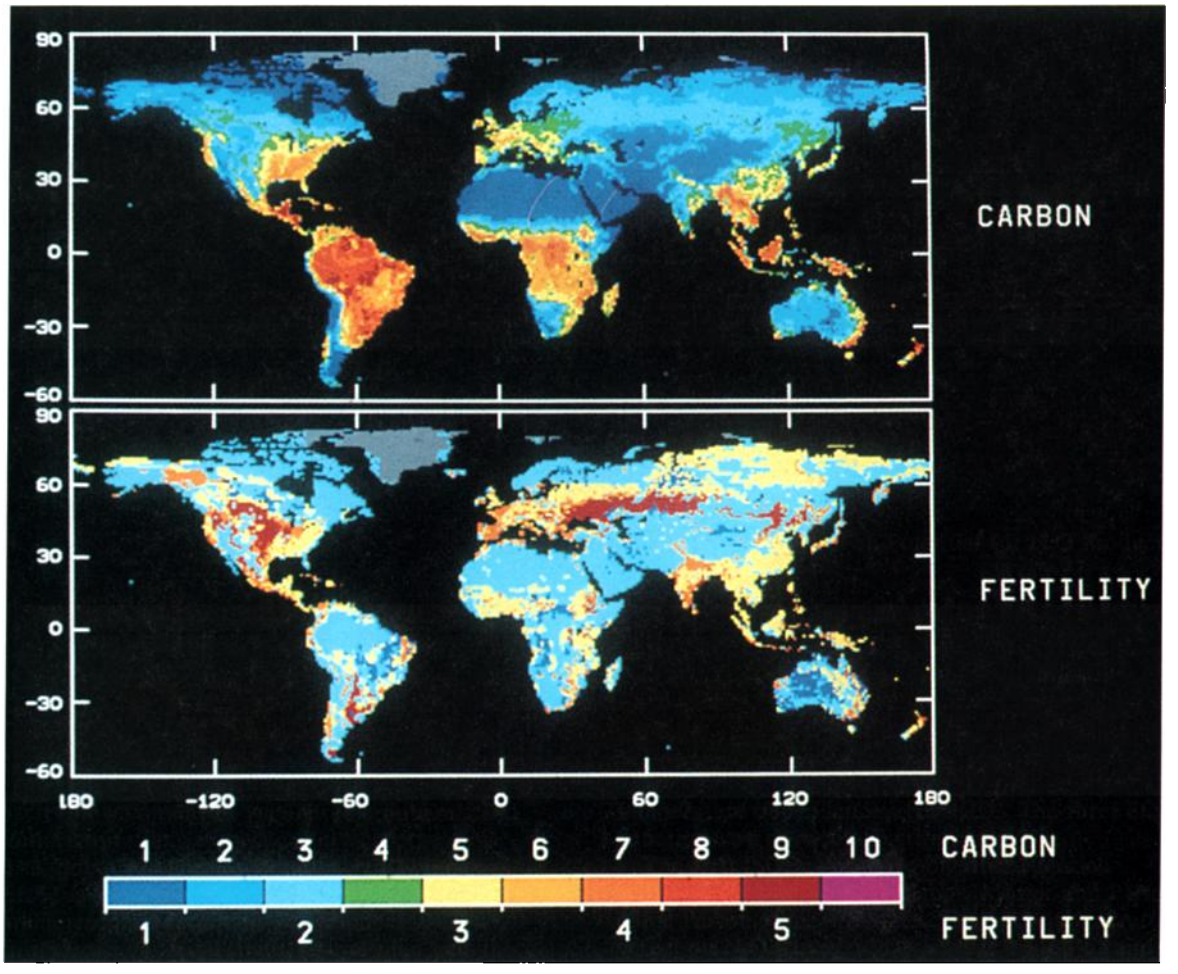

Plate 2. Distribution of factors used in the model: CARBON (upper panel), representing the input of organic matter, is NDVI scaled from 0-10, and FERT (lower panel), soil fertility, scaled from 1-5 (see Table 1).

of the cation exchange capacity [FAO/Unesco, 1974-1981]. In general, leached soils in wet climates have lower fertility than soils with a less pronounced downward flow of water over the year. Ferralsols (soil group 13) are strongly leached soils with variable charge characteristics, dominated by kaolinite and hydrated oxides of alumina and iron; their fertility is low due to low cation exchange capacity, the presence of alumina at the exchange complex, low content of weatherable minerals and phosphorous fixation. Podzols (soil group 2) are also infertile, generally because of low cation exchange capacity, low content of weatherable minerals and alumina saturation.

The global distribution of soil fertility index (FERT) is shown in Plate 2. Globally, soils are characterized predominantly by moderately low fertility: soils covering slightly more than half the ice-free land area have fertility indices of two. About one quarter of the land is of intermediate fertility, while the other fertility classes account for <10% each.

Temperature effect on rate of soil organic matter decomposition and N mineralization (SOD). Rates of decomposition and nitrogen mineralization are regulated by a number of soil factors including temperature, moisture, fertility, and texture. All these factors, except soil temperature, are represented in the factors H2O and FERT. Lacking a global data set on soil temperatures, we use monthly climatologies of surface air temperature [Shea, 1986]; this might introduce timing errors of up to 1-2 months particularly in middle to high latitudes. In this study, we investigated three temperature dependencies for SOD. The three SOD functions are shown in Figure 2.

The first (SOD1) is an exponential function obtained for semiarid grasslands [Mosier and Parton, 1985; Parton et al., 1988] describing the temperature effect on N_2O fluxes: SOD1 = 10 at T = 50°C, and SOD1 = 0 for T < 0°C, with a rapid increase between 10° and 30°C. The second equation (SOD2) is a quadratic function adapted from Parton et al. [1987] describing decomposition of soil organic matter in

TABLE 1. Indices of Soil Fertility (FERT) and Drainage (DRNG) Assigned to Different Soil Units

	Soil Unit	FERT	DRNG	Area (10^6 ha)
I	SOILS WITH PERMAFROST			674
1	Soils with permafrost within 200 cm			674
	gelic Cambisols	3	5	232
	gelic Gleysols	3	5	148
	gelic Histosols	2	5	66
	gelic Planosols	2	5	-
	gelic Regosols	2	5	228
II	SOILS CONDITIONED BY SUBHUMID CLIMATES			885
2	Soils with illuviation of organic matter and/or sesquioxides			493
	ferric Podzols	2	1	-
	gleyic Podzols	2	3	44
	humic Podzols	2	1	31
	leptic Podzols	2	1	19
	orthic Podzols	2	1	398
	placic Podzols	2	2	1
3	Soils with strong textural differentiation with slowly permeable subsoil			141
	dystric Planosols	1	3	1
	eutric Planosols	2	3	63
	humic Planosols	2	3	1
	mollic Planosols	2	3	16
	solodic Planosols	1	3	60
4	Soils with argic horizon* underlying a bleached subsurface horizon			251
	dystric Podzoluvisols	2	2	66
	eutric Podzoluvisols	3	2	159
	gleyic Podzoluvisols	3	3	26
III	SOILS CONDITIONED BY DRY SUBHUMID (SUB-) TROPICAL OR SUBHUMID TEMPERATE CLIMATES			950
5	Soils with argic horizon*			950
	albic Luvisols	3	2	114
	calcic Luvisols	4	2	63
	chromic Luvisols	4	2	249
	ferric Luvisols	3	2	264
	gleyic Luvisols	4	3	73
	orthic Luvisols	4	2	162
	plinthic Luvisols	3	4	23
	vertic Luvisols	4	3	2
IV	SOILS CONDITIONED BY STEPPE CLIMATES			897
6	Soils with argic horizon* and organic matter accumulation			27
	gleyic Greyzems	3	3	11
	orthic Greyzems	3	2	17
7	Soils with organic matter accumulation, annual precipitation > evapotranspiration			153
	calcaric Phaeozems	5	1	4
	gleyic Phaeozems	5	3	11
	haplic Phaeozems	5	1	58
	luvic Phaeozems	5	2	80
8	Soils with organic matter accumulation, annual precipitation = evapotranspiration			225
	calcic Chernozems	5	1	32
	glossic Chernozems	5	1	6
	haplic Chernozems	5	1	124
	luvic Chernozems	5	2	63

TABLE 1. (continued)

	Soil Unit	FERT	DRNG	Area (10^6 ha)
9	Soils with organic matter accumulation, annual precipitation < evapotranspiration			492
	calcic Kastanozems	5	1	14
	haplic Kastanozems	5	1	225
	luvic Kastanozems	5	2	253
V	SOILS CONDITIONED BY LIMITED AGE			758
10	Weakly developed soils			758
	calcic Cambisols	4	1	86
	chromic Cambisols	3	1	81
	dystric Cambisols	3	1	245
	eutric Cambisols	4	1	230
	ferralic Cambisols	3	1	23
	gleyic Cambisols	3	3	15
	humic Cambisols	4	1	60
	vertic Cambisols	4	2	18
VI	SOILS CONDITIONED BY WET (SUB-) TROPICAL CLIMATES			2228
11	Leached soils with argic horizon*			903
	ferric Acrisols	3	2	164
	gleyic Acrisols	2	3	40
	humic Acrisols	3	2	41
	orthic Acrisols	3	2	576
	plinthic Acrisols	2	4	82
12	Strongly weathered soils with deeply developed argic horizon*			209
	dystric Nitosols	3	1	114
	eutric Nitosols	5	1	80
	humic Nitosols	5	1	15
13	Strongly leached soils dominated by hydrated oxides			1116
	acric Ferralsols	1	1	68
	humic Ferralsols	2	1	27
	orthic Ferralsols	2	1	506
	plinthic Ferralsols	1	4	38
	rhodic Ferralsols	2	1	73
	xanthic Ferralsols	2	1	404
VII	SOILS CONDITIONED BY (SEMI-)ARID CLIMATES			2108
14	Desert soils			1876
	calcic Xerosols	2	1	253
	calcic Yermosols	2	1	314
	gypsic Yermosols	2	1	69
	haplic Yermosols	2	1	743
	gypsic Xerosols	2	1	6
	haplic Xerosols	2	1	133
	luvic Xerosols	2	2	107
	luvic Yermosols	2	2	235
	takyric Yermosols	2	1	16
15	Saline and alkaline soils			232
	gleyic Solonchaks	1	3	27
	mollic Solonchaks	2	1	5
	orthic Solonchaks	1	1	92
	takyric Solonchaks	1	1	3
	gleyic Solonetz	1	4	1
	mollic Solonetz	2	3	29
	orthic Solonetz	1	3	75
VIII	SOILS CONDITIONED BY THEIR PARENT MATERIAL			1146
16	Heavy textured cracking soils dominated by clays with swell-shrink properties			314
	chromic Vertisols	3	3	205
	pellic Vertisols	3	3	109

TABLE 1. (continued)

	Soil Unit	FERT	DRNG	Area (10^6 ha)	
17	Soils formed in volcanic ash				111
	humic Andosols	4	1	20	
	mollic Andosols	4	1	12	
	ochric Andosols	4	1	27	
	vitric Andosols	4	1	52	
18	Weakly developed soils with sand texture				721
	albic Arenosols	1	1	19	
	cambic Arenosols	2	1	316	
	ferralic Arenosols	1	1	302	
	luvic Arenosols	2	2	84	
IX	SOILS CONDITIONED BY THEIR PHYSIOGRAPHIC POSITION				3377
19	Soils influenced by a floodplain regime				245
	calcaric Fluvisols	4	1	61	
	dystric Fluvisols	3	1	35	
	eutric Fluvisols	4	1	138	
	thionic Fluvisols	1	5	11	
20	Soils influenced by groundwater				412
	calcaric Gleysols	3	5	16	
	dystric Gleysols	2	5	161	
	eutric Gleysols	3	5	134	
	humic Gleysols	3	5	27	
	mollic Gleysols	3	5	72	
	plinthic Gleysols	2	5	2	
21	Leptosols (shallow soils, mostly <10 cm thick)				2273
	Lithosols	2	1	2224	
	Rankers	1	1	3	
	Rendzinas	3	1	46	
22	Weakly developed soils formed in unconsolidated non-alluvial material				447
	calcaric Regosols	2	1	189	
	dystric Regosols	1	1	87	
	eutric Regosols	3	1	171	
X	ORGANIC SOILS				172
23	Histosols (peat soils)				172
	dystric Histosols	1	5	125	
	eutric Histosols	2	5	47	

Low index values indicate low fertility and free drainage. Soil units are classified by soil groups (arabic numbers) and soil clusters (roman numbers); the areas of each unit is given in column 4, while those of each group and cluster are in column 5. Total ice-free land area is $13{,}195 \times 10^6$ ha. Land ice is 1666×10^6 ha.

* argic horizon = subsurface horizon with distinctly higher clay content than overlying horizon.

grasslands. The optimum (SOD2 = 10) is at T = 33°C. To avoid negative values, SOD2 is set to zero at T < 0°C and at T > 49°C. The third relationship (SOD3) is a set of linear functions for four broad ecosystem groups: broadleaf vegetation, needleleaf vegetation, grassland, and tropical vegetation. The functions are derived from observations of CO_2 evolution from soils and mean monthly temperature [Fung et al., 1987]: SOD3 = 10 at T = 50°C. The different slopes of the four functions reflect the differences in litter composition for the broad biome groups. For comparable temperature ranges, grassland, with a high fraction of easily decomposable detrital material, has a faster relative decomposition rate than that of needleleaf woody vegetation.

Differences between the SOD1 and SOD2 functions are minor: the most marked differences are expected in temperate climates with mild winters. At temperatures between 0° and 10°C, SOD2 yields the lowest values; in that temperature range, SOD3 gives much higher values than the other functions.

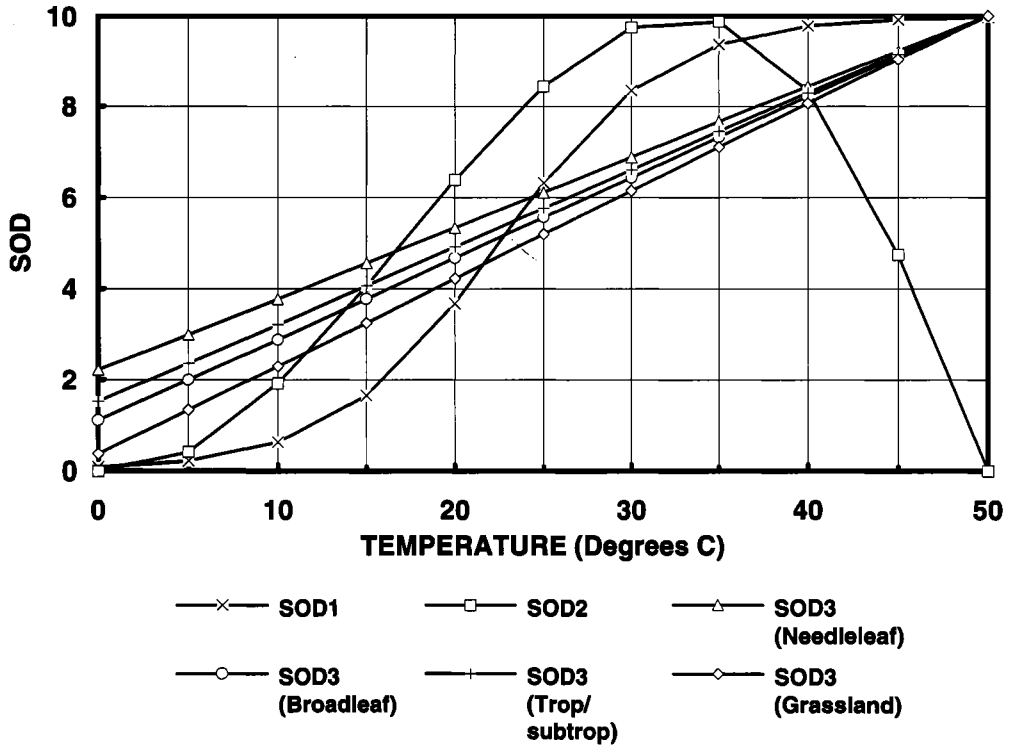

Fig. 2. Index of the rates of soil organic matter decomposition and N mineralization (SOD) as a function of temperature. SOD1 (reference) is taken from Mosier and Parton [1985] and Parton et al. [1988]; SOD2 from Parton et al. [1987]; SOD3 from Fung et al. [1987].

The three functions give similar results for the tropics. The SOD1 equation yields the best correlation with the measurement data (see Section 4.4). For that reason, SOD1 was chosen as the reference case. The global distribution of SOD1 is shown in Plate 3 (annual total of the monthly values).

Soil water and soil oxygen. A key to determining moisture conditions for decomposition and for distinguishing the pathways of nitrification versus denitrification is the degree of saturation and aerobicity of the soil which are determined by the soil water content (SWC) and its relation to the maximum amount of water held in the soil [soil water storage capacity, SSC), and by soil drainage properties. Topsoils are the primary sites for N_2O production since maximum microbial activity and the most intensive rooting occur in this soil layer. Nitrification may dominate in the upper few millimeters [Seiler and Conrad, 1981] while denitrification may dominate below, particularly during periods of high water content [Goodroad and Keeney, 1985]. Therefore, we consider the topsoil, i.e. upper 30 cm of soil, as the zone of N_2O production. Some physical properties in zones below 30 cm, that influence water and air movement in the topsoil, are included in the soil drainage characteristics.

Soil water storage capacity (SSC). Soil water storage capacity is the maximum amount of water held in the upper 30 cm of the soil at field capacity (soil water potential of 10 kPa = 0.1 bar), i.e. when internal drainage and redistribution have ceased. In reality, redistribution of water after wetting is continuous and the field capacity is reached after prolonged periods if at all. Nevertheless, for the scale and purpose of this study, the above definition of SSC is appropriate.

SSC values are listed in Table 2. For most soils, water storage capacity is derived from soil texture based on average soil physical characteristics of major texture classes [Euroconsult, 1989; Landon, 1984]. The global distributions of soil texture and SSC are shown in Plate 4. For several soils with special physical properties influencing field capacity, alternative water storage capacities are assigned regardless of soil texture. These are discussed in some detail, since the soils involved cover about 30% of the ice-free land surface of the Earth.

Vertisols (Table 1) are cracking clay soils dominated by montmorillonitic clays with swell-shrink properties. Their water storage capacity may be lower than expected on the basis of their clay content because it is usually difficult to wet these soils. After the initial rain, infiltration rates may decrease as the clay swells and closes the cracks [see Blokhuis, 1991]. On the basis of these characteristics, Vertisols are assigned a low storage capacity similar to coarse- and medium-textured

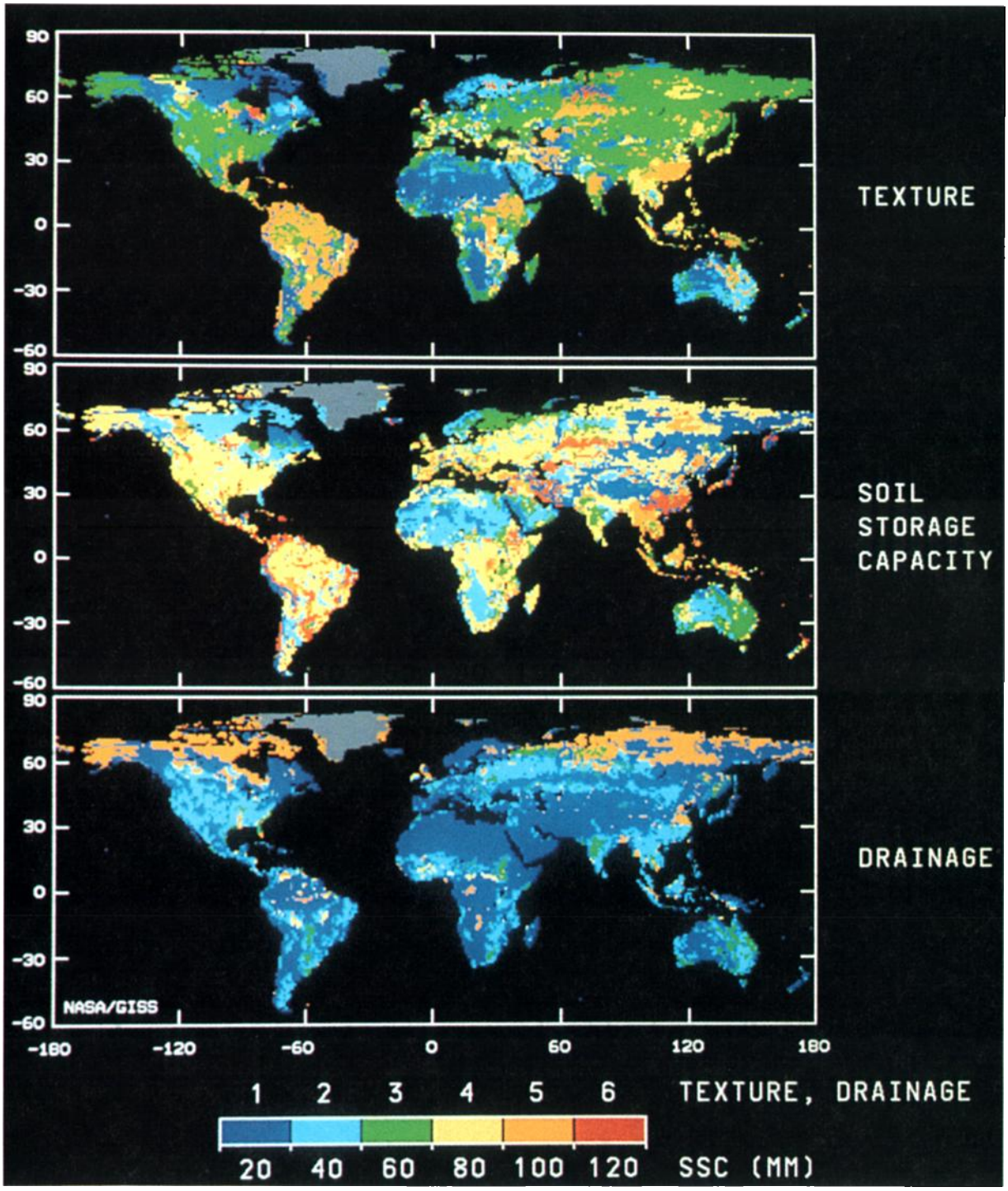

Plate 3. Distribution of soil characteristics derived from the soil data base. Texture class (upper panel) determines the soil storage capacity (SSC; middle panel). Refer to Table 2 for descriptions of numbered texture classes and soil storage capacity. Drainage indices (lower panel) for soil units are listed in Table 1.

TABLE 2. Soil Water Storage Capacity (SSC) of the Upper 30 cm

Texture Class	Soil Texture	SSC [a]	γ [b]	δ, [b] mm
1	coarse	40	15	0
2	coarse/medium	60	9	0
6	organic	60	18	0
3	coarse/fine	80	9	0
3	coarse/medium/fine	80	9	0
3	medium	80	9	0
4	medium/fine	100	9	0.1
5	fine	120	6	0.1
	Soil Type[c]	SSC	γ [b]	δ, [b] mm
	Rendzinas	15	15	0
	Lithosols	15	15	0
	Rankers	15	15	0
	Vertisols	60	6	0.1
	vertic Cambisols	80	9	0.1
	Ferralsols	80	9	0
	vertic Luvisols	80	9	0.1
	Andosols	120	9	0

[a] SSC is shown for major texture classes [Zobler, 1986] and for some soil types [FAO/Unesco, 1974-1981] with limited soil depth or clay minerals having specific soil-moisture retention characteristics. Based on Landon [1984] and Euroconsult [1989].

[b] γ and δ are used in Eqn. (2) in the computation of transpiration and soil evaporation from the soil-water content; δ expresses the intercept of the soil-water extraction curve β.

[c] A full list of soil units and their fertility and drainage indices is presented in Table 1.

soils. In addition, soil units with vertic properties are assigned SSC values similar to those of medium-textured soils.

Because particle size distributions of Andosols and Ferralsols are not easily determined [Dijkerman, 1991], texture information from the FAO/Unesco maps may be less reliable than for other soil groups. In Ferralsols, positively charged hydrated oxides and negatively charged kaolinite form stable aggregates with many biopores resulting in water retention characteristics similar to those of sands or medium-textured soils, although some Ferralsols are fine-textured. Ferralsols are assigned a water-storage capacity of 80 mm, equal to that of medium-textured soils.

Andosols are soils formed in volcanic ash, commonly with high aggregate stability. Water availability in Andosols is generally not lower, and is often higher, than in other mineral soil materials [Van Reeuwijk, 1991], which may not be reflected by their texture. Therefore Andosols are assigned a topsoil storage capacity of 120 mm, equal to SSC values for fine textures.

Leptosols, shallow soils with a depth of ~10 cm or less, are assigned a low storage capacity of 15 mm since their shallowness is assumed to exert primary influence on water storage.

Soil water budget model. The monthly change in soil moisture is the difference between the supply, and demand of moisture at the surface. Supply is governed mainly by precipitation, while demand is governed by evaporation from soils and transpiration by plants.

Several soil moisture models are used in general circulation models, ranging from the simple bucket model of Manabe [1969], where SSC is uniformly 15 cm, to the simple biosphere model (SiB) of Sellers et al. [1986] and the complex biosphere-atmosphere scheme (BATS) of Dickinson et al. [1986] which take into account differential effects of biomes on soil-water balance. The recent models distinguish soil evaporation from plant evaporation and transpiration, as well as model explicitly vertical profiles of soil moisture. We note that in a bucket model where supply and demand are independent of soil moisture itself, the solution to the soil moisture equation is not uniquely determined; it is dependent on the initial soil water content assumed unless SWC = 0 or SWC = SSC (runoff) sometime during the year.

We employed a simple soil-moisture model whose solution does not depend on an arbitrarily chosen initial condition. We adapted the Mintz and Serafini [1981] model for calculating monthly soil-water content. In this model, net supply is the difference between monthly precipitation (P_m) and evaporation from wet canopies (EI_m), while demand is the sum of transpiration through plants and evaporation from soils (ETS_m).

$$SWC_m = SWC_{m-1} + (P_m - EI_m) - ETS_m \quad (1)$$

Potential evapotranspiration (PE_m), maximum moisture demand by the atmosphere, is calculated from the surface air temperature according to Thornthwaite [1948]. Mean monthly surface air temperatures (T_m) and precipitation (P_m) are obtained from Shea [1986]. Three moisture regimes are considered, depending on the relation between precipitation and potential evapotranspiration:

$$\begin{aligned} P_m = 0 \quad & EI_m = 0 \\ & ETS_m = PE_m \times \beta_m \times \alpha \\ P_m < PE_m \quad & EI_m = P_m \\ & ETS_m = (PE_m - P_m) \times \beta_m \times \alpha \quad (2) \\ P_m \geq PE_m \quad & EI_m = PE_m \\ & ETS_m = 0 \end{aligned}$$

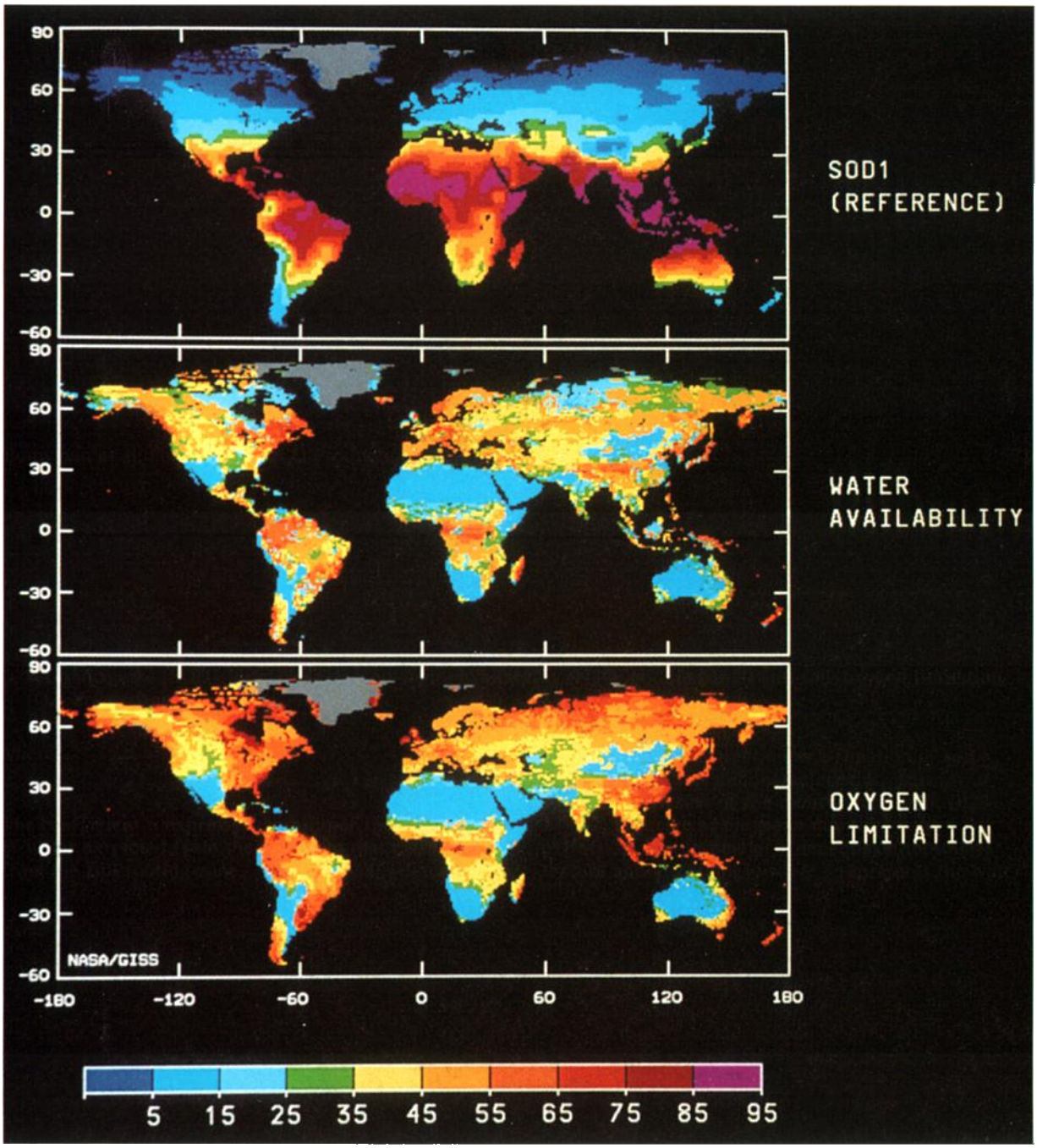

Plate 4. Distribution of annual sums of monthly indices for soil organic matter decomposition for the reference case (SOD1; upper panel), soil-water availability (H2O; middle panel) and soil-oxygen limitation (O2; lower panel).

where $\alpha = 0.4$ and

$$\beta_m = 1 - e^{-\gamma[\{SWC_{m-1} + (P_m - EI_m)/2\}/SSC - \delta]}$$

The coefficient α expresses the ratio of the amount of water extracted from the topsoil to that extracted from the full rooting zone. The function β describes maximum water extraction as a function of soil water content and soil characteristics. It is calculated for 50% of the monthly addition, $(P_m - EI_m)/2$, to arrive at the mean monthly water extraction. Its parameter γ depends on topsoil texture and mineralogy, while δ represents the water

unavailable to plants, i.e. the intercept of the water extraction curve β. The values of δ and γ (Table 2) are based on Hillel [1980]. For clays, $\gamma = 6$, resulting in a strong decrease in water extraction below SWC/SSC about 50%. Due to the selected value of δ for clays, water extraction at SWC/SSC < 10% is reduced. In sands and medium-textured soils, β sharply decreases at values of SWC/SSC of about 40% and 20%, respectively. Because SWC is a function of β, the monthly equilibrium SWC is achieved independently of the initial water content at the start of the simulation.

Effects of Soil Drainage (DRNG). In the calculation of soil-water content above, drainage properties are not considered. Drainage is a soil property that determines the removal of excess water from the soil, and is an indicator of soil aeration. Soil drainage indices are used to estimate soil-water status and are prescribed for soil units on the basis of several soil properties including the presence of impermeable and less permeable horizons (Table 1). The global distribution of the drainage index (DRNG) is shown in Plate 4. We recognize that the soil data base may not represent the local spatial variations in drainage (see appendix), particularly for small areas of hydromorphic soils which may be important for N_2O fluxes.

Very poorly drained soils (DRNG = 5) include those soil groups strongly influenced by groundwater such as the Gleysols and Histosols, as well as soils with permafrost within 200 cm of the soil surface (gelic soil units). Soils with somewhat impeded drainage and moderately restricted aeration (DRNG = 4) include gleyic Solonetz and soils with plinthite; plinthic Acrisols and plinthic Ferralsols are wet tropical soils, usually with fluctuating water tables, and with firm plinthic subsurface layers within 50-125 cm of the surface that are iron-rich and humus-poor. Gleyic Solonetz are compact soils with hydromorphic properties and clay in the subsoil. The intermediate class (DRNG=3) indicates impeded drainage and restricted aeration; it encompasses gleyic soil units (in which only the subsoil is influenced by groundwater or with a seasonally perched water table within the profile), Planosols (a slowly permeable subsoil), Vertisols (soils with swell/shrinkage properties and montmorillonitic clays dominating the clay fraction) and the nongleyic Solonetz (compact alkaline soils with a natric horizon). About 20% of the land surface, with a drainage index of 2, comprises soils with an increase in clay content in the subsoil (argic horizon), [FAO/Unesco, 1988]. Water stagnation and anaerobic conditions may occur in these soils during periods of high precipitation. About two thirds of the land lacks the above properties and is considered freely drained (DRNG=1). The effects of drainage on soil oxygen limitation and water availability are difficult to quantify. The drainage indices are used to estimate soil water status.

Soil-Water Status (SWS). Soil-water status of the topsoil is scaled on the basis of soil-water content and drainage as shown in Table 3. Although it is difficult to combine drainage and soil-water status at their intermediate values in the index, we note several points: (1) distinguishing saturation levels <20% is not important; (2) we increase the SWS scale linearly up to the saturation; (3) we fill in the rest of the table by assuming that N_2O production likely asymptotes at high saturation and poor drainage. While it is clear that the highest SWS rank of 10 should be assigned to a poorly drained soil when the monthly soil-water content approaches storage capacity, the SWS scale is somewhat arbitrary. It represents a first attempt at quantifying our understanding of the effects of soil drainage characteristics on soil oxygen and soil moisture.

TABLE 3. Scaled Soil-Water Status (SWS) as a Function of Soil Drainage (DRNG; see Table 1) and Modeled Soil-Water Content/Soil-Water Storage Capacity (SWC/SSC; see Table 2)

		Drainage Scale (DRNG)				
	SWC/SSC, %	1	2	3	4	5
1	0 - 20	1	1	1	1	2
2	20 - 30	2	2	2	2	3
3	30 - 40	3	3	3	4	5
4	40 - 50	4	4	4	5	7
5	50 - 60	5	5	5	6	8
6	60 - 70	6	6	6	7	9
7	70 - 80	6	7	7	8	9
8	80 - 90	7	7	8	9	10
9	90 -100	7	8	9	10	10
10	surplus (>100%)	8	9	10	10	10

Effects of water status and oxygen status on decomposition, nitrification and denitrification. Two factors are derived to describe these effects: water availability (H2O) and oxygen limitation (O2). H2O describes the influence of soil water on decomposition, mineralization and nitrification processes. In general, water contents of 60-80% of field capacity are favorable for these processes while nearly saturated and anaerobic soils have low H2O values [Linn and Doran, 1984; Davidson, 1991]. H2O (Table 4) is based on the soil-water status of the previous and current months. Wetting of dry soils is assumed to be more favorable, and drying soils less favorable, than are conditions of constant water content [Groffman and Tiedje, 1988]. Although we do not attempt to simulate the reported pulses in N_2O production after the wetting of dry soils, we hypothesize that pulses of N_2O at the onset of a wet season give a higher average monthly N_2O flux than in wet months preceded by moist conditions.

TABLE 4. Scaled Soil Water Availability (H2O) for the Reference Case and Experiments 1-5 and 7

SWS in Preceding Month	SWS in Current Month 1	2	3	4	5	6	7	8	9	10
1	1	2	4	6	9	10	10	10	6	1
2	1	1	3	5	8	9	10	10	6	1
3	1	1	2	4	7	8	9	10	5	1
4	1	1	2	4	7	8	8	8	4	1
5	1	1	2	4	6	7	7	7	3	1
6	1	1	2	4	6	7	7	6	2	1
7	1	1	2	4	6	7	7	6	2	1
8	1	1	2	4	5	6	6	5	2	1
9	1	1	2	3	4	6	6	4	2	1
10	1	1	2	3	4	5	6	4	2	1

H2O is a function of soil-water status (SWS, see Table 3) of the current month and of the preceding month. The H2O scale corresponding to SWS in the current month only, used in experiment 6, is given by the underlined numbers on the diagonal of the table (see Table 5).

TABLE 5. Scaled Oxygen Limitation (O2) for the Reference Case and Experiments 1-5 and 7

SWS in Preceding Month	SWS in Current Month 1	2	3	4	5	6	7	8	9	10
1	1	1	1	4	6	8	10	10	10	10
2	1	1	1	4	6	8	10	10	10	10
3	1	1	1	3	5	7	9	10	10	10
4	1	1	1	3	4	6	8	9	10	10
5	1	1	1	2	3	5	7	8	9	10
6	1	1	1	1	2	4	6	7	8	9
7	1	1	1	1	2	3	5	6	7	8
8	1	1	1	1	2	3	4	5	6	7
9	1	1	1	1	2	3	4	5	6	7
10	1	1	1	1	2	3	4	5	6	7

O2 is a function of the soil-water status (SWS, see Table 3) of the current month and of the preceding month. The O2 scale used in experiment 6, which is a function of SWS in the current month only, is given by the underlined numbers on the diagonal of the table.

The regulator O2 expresses effects of soil-oxygen status on denitrification. It is obtained from the soil-water status of the previous and current months (Table 5) and includes the effect of wetting and drying of soils. Oxygen limitation at soil-water contents of 60-80% is treated as most favorable for N_2O production by nitrification while denitrification is more prominent at water contents of >80%. In general, high levels of wetness result in greater oxygen limitation; wetting of dry soils is assigned higher O2 indices than constantly wet or moist soils. The information in H2O and O2 is very similar at SWC values between 7 and 9. Under saturated conditions, low H2O counteracts high O2 values reflecting the simultaneous occurrence of conditions favorable for denitrification (O2), and unfavorable for NH_4^+ oxidation by nitrification. In one sensitivity experiment, only the current month determines H2O and O2; in that case the H2O and O2 scales are the diagonals in Tables 4 and 5, respectively. Annual sums of monthly H2O and O2 are shown in Plate 3.

N_2O production (N2O). The controls on N_2O fluxes identified above are combined to yield monthly nondimensional N_2O indices at 1° resolution for the globe. We recognize that the five factors chosen are not independent. In particular, CARBON, scaled from the annual integral of the NDVI, captures geographic variations in temperature, soil moisture, and soil fertility.

There are many ways to combine the factors. Lacking information about relative importance, we assume that all five controlling factors are of equal importance, i.e. the maximum fertility factor has the same effect as the maximum oxygen limitation factor as far as N_2O production is concerned. Hence, although FERT is scaled from 1 to 5 because of our inability to discriminate further, FERT is multiplied by two (FERT*) to normalize to the other factors.

We model the nondimensional monthly N_2O production as the geometric mean of the five controlling factors. In this way, a low value for one of the factors automatically lowers the N_2O production index. For example, values of 1 and 9 for two factors are given less weight than 5 and 5, which yields the same arithmetic mean.

It is difficult to rank the above regulators a priori since the influences of these regulators varies among habitats [Tiedje, 1988]. Therefore the monthly nondimensional N_2O production index, N2O is calculated for the reference case as:

$$N2O = [O2 \times H2O \times SOD \times FERT^* \times CARBON]^{1/5} \quad (3)$$

where N2O, O2, H2O, and SOD are indices calculated monthly, and FERT* and CARBON are site characteristics constant for every month. Under conditions where soil processes are inactive (months in which mean surface temperatures < 0°C), N2O is set to zero. N2O is also set to zero for months in which the monthly precipitation ≤ 5.0 mm and the soil-water content is ≤ 1%. When there is rainfall (P > 0) and the water budget equation predicts a dry

TABLE 6a. Mean and Standard Deviation of Modeled N2O by Soil Group in the Tropics and Subtropics for the Reference Case and Seven Sensitivity Experiments

Soil Group	Area 10^6ha	REF	E1	E2	E3	E4	E5	E6	E7
2A	15	50	48	49	52	52	61	50	60
		(19)	(21)	(21)	(25)	(22)	(20)	(20)	(33)
3A	95	38	35	33	39	41	45	38	69
		(28)	(34)	(29)	(30)	(28)	(29)	(28)	(34)
5A	546	44	41	43	38	49	44	43	54
		(26)	(33)	(25)	(32)	(25)	(26)	(27)	(43)
7A	15	53	56	51	45	56	48	53	73
		(21)	(30)	(19)	(28)	(17)	(28)	(22)	(33)
9A	75	39	38	36	31	48	31	38	60
		(35)	(43)	(36)	(44)	(30)	(38)	(36)	(42)
10A	290	53	53	53	49	58	50	53	61
		(25)	(29)	(25)	(30)	(22)	(28)	(26)	(37)
11A	736	52	52	50	50	54	56	52	74
		(15)	(18)	(16)	(18)	(17)	(17)	(15)	(25)
12A	204	58	56	57	52	64	52	57	66
		(18)	(23)	(16)	(22)	(16)	(17)	(19)	(29)
13A	1113	56	52	51	60	59	58	56	82
		(16)	(16)	(16)	(16)	(15)	(13)	(17)	(18)
14A	1008	12	10	12	10	14	14	12	11
		(87)	(105)	(86)	(93)	(90)	(80)	(86)	(134)
15A	84	24	19	25	25	25	29	24	26
		(41)	(59)	(35)	(46)	(39)	(53)	(41)	(87)
16A	281	39	36	42	35	41	36	37	35
		(19)	(21)	(16)	(22)	(18)	(28)	(19)	(52)
17A	49	53	54	53	46	59	48	53	59
		(29)	(31)	(30)	(36)	(27)	(33)	(29)	(29)
18A	696	25	22	24	27	28	31	25	34
		(50)	(60)	(45)	(60)	(46)	(47)	(50)	(77)
19A	132	48	47	49	43	52	45	47	51
		(39)	(44)	(38)	(44)	(37)	(43)	(40)	(49)
20A	162	45	42	44	43	45	55	45	64
		(21)	(22)	(20)	(24)	(21)	(22)	(21)	(38)
21A	752	23	21	21	21	24	26	22	27
		(78)	(89)	(76)	(86)	(78)	(74)	(78)	(106)
22A	330	18	15	19	17	21	22	18	16
		(65)	(75)	(58)	(71)	(62)	(59)	(64)	(107)
23A	39	43	38	39	45	38	66	43	64
		(17)	(16)	(17)	(17)	(21)	(16)	(17)	(33)

Standard deviations are in parentheses and are expressed as a percent of the mean N_2O index of each soil group for each experiment.

soil at the end of that month (SWC = 0), the soil has not been dry throughout the month. In that case the indices for O2 and H2O are low, giving low N2O.

4. RESULTS AND DISCUSSION

The model was run globally at 1° resolution for 12 months. Model results for the reference case are discussed in section 4.1; sensitivity experiments analyzing the relative importance of the five factors are discussed in 4.2, and results for selected sites are described in section 4.3. Results are compared with measurements in section 4.4 and used to estimate a global flux in section 4.5.

4.1. *Global Results for the Reference Case*

The mean annual sum of N2O and its standard deviation (expressed as percentage of the mean) is presented for the reference case and the experiments for the 23 soil groups (Table 6). The standard deviation reflects the variation in annual sums over

TABLE 6b. Like Table 6a, but for Temperate and Subpolar Latitudes

Soil Group	Area 10^6ha	REF	E1	E2	E3	E4	E5	E6	E7
1B	674	3	9	3	2	3	3	3	7
		(106)	(42)	(106)	(117)	(102)	(99)	(106)	(61)
2B	478	10	25	9	9	10	12	10	22
		(64)	(45)	(72)	(79)	(62)	(62)	(62)	(60)
3B	46	29	36	26	30	29	35	29	57
		(29)	(24)	(26)	(33)	(26)	(31)	(29)	(36)
4B	251	10	21	10	9	11	10	11	21
		(32)	(28)	(33)	(36)	(33)	(30)	(33)	(33)
5B	404	22	37	21	19	24	20	23	40
		(48)	(35)	(47)	(49)	(45)	(44)	(45)	(45)
6B	27	11	22	11	10	13	11	12	23
		(24)	(18)	(23)	(23)	(19)	(22)	(25)	(20)
7B	138	31	48	30	25	34	27	32	52
		(48)	(33)	(44)	(53)	(42)	(48)	(46)	(43)
8B	225	15	25	16	11	17	13	15	21
		(23)	(29)	(22)	(24)	(20)	(23)	(24)	(30)
9B	417	15	25	17	11	18	14	16	21
		(43)	(46)	(35)	(47)	(42)	(35)	(42)	(69)
10B	468	21	38	21	18	23	19	22	36
		(63)	(52)	(62)	(69)	(62)	(58)	(62)	(62)
11B	166	36	54	32	34	37	36	36	72
		(27)	(13)	(29)	(30)	(26)	(32)	(27)	(20)
12B	5	52	66	45	47	53	44	52	79
		(23)	(9)	(26)	(26)	(26)	(29)	(22)	(23)
13B	3	49	56	43	48	48	46	50	76
		(12)	(10)	(14)	(16)	(8)	(15)	(11)	(18)
14B	868	15	19	16	12	16	16	15	15
		(46)	(54)	(48)	(57)	(49)	(43)	(45)	(75)
15B	148	16	19	17	16	16	16	16	19
		(58)	(56)	(52)	(64)	(52)	(71)	(58)	(102)
16B	33	38	45	37	34	37	37	37	54
		(22)	(16)	(18)	(26)	(18)	(30)	(23)	(45)
17B	62	23	50	23	20	24	20	24	43
		(65)	(34)	(62)	(70)	(63)	(67)	(65)	(62)
18B	25	18	25	18	17	19	21	19	25
		(55)	(39)	(51)	(63)	(57)	(48)	(51)	(74)
19B	114	16	25	16	12	17	14	15	21
		(82)	(67)	(79)	(93)	(79)	(73)	(80)	(86)
20B	250	14	24	13	11	13	14	14	24
		(77)	(58)	(83)	(88)	(72)	(85)	(76)	(77)
21B	1521	9	18	8	7	9	11	9	16
		(86)	(67)	(92)	(101)	(81)	(78)	(86)	(83)
22B	117	18	27	18	15	20	18	18	24
		(50)	(40)	(50)	(58)	(48)	(45)	(48)	(58)
23B	133	7	15	7	7	7	9	7	17
		(58)	(42)	(61)	(60)	(51)	(56)	(58)	(48)

the areal extent of each soil group. Note that the SOD1 function is used in all cases. The results for the soil groups are presented separately for the tropics (Table 6a; within 30° of the equator) and the extratropics (Table 6b; poleward of 30° latitude). The annual sum of monthly N_2O indices for the reference case is shown in Plate 5; the latitudinal and seasonal distribution of N2O is shown in Figure 3. Since the index can range from 0 to 10 in any month, the potential annual maximum is 120, although the actual maximum is 84. The results for the reference case suggest that the wet tropics and

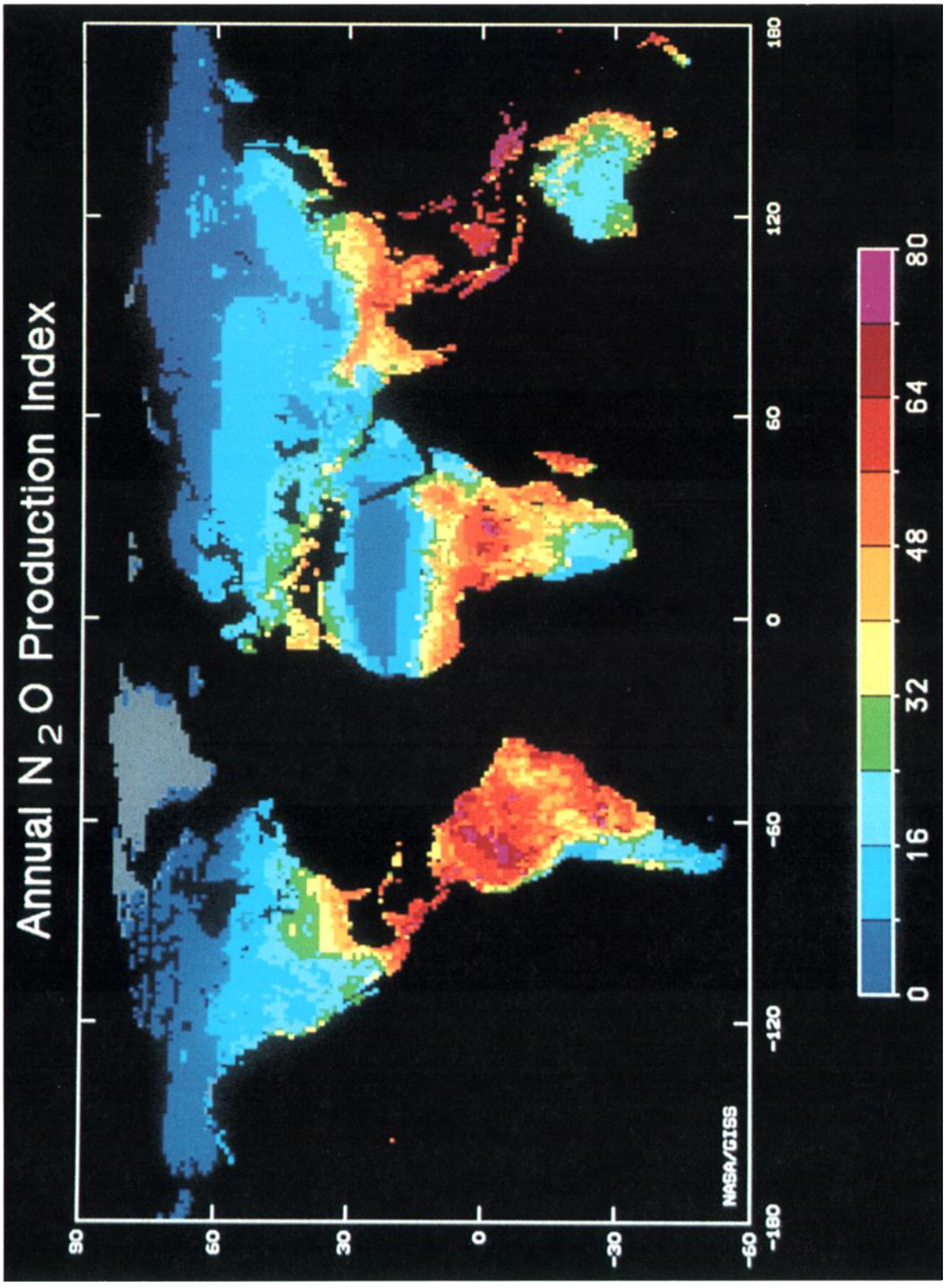

Plate 5 Distribution of annual sum of monthly N_2O production potential N2O.

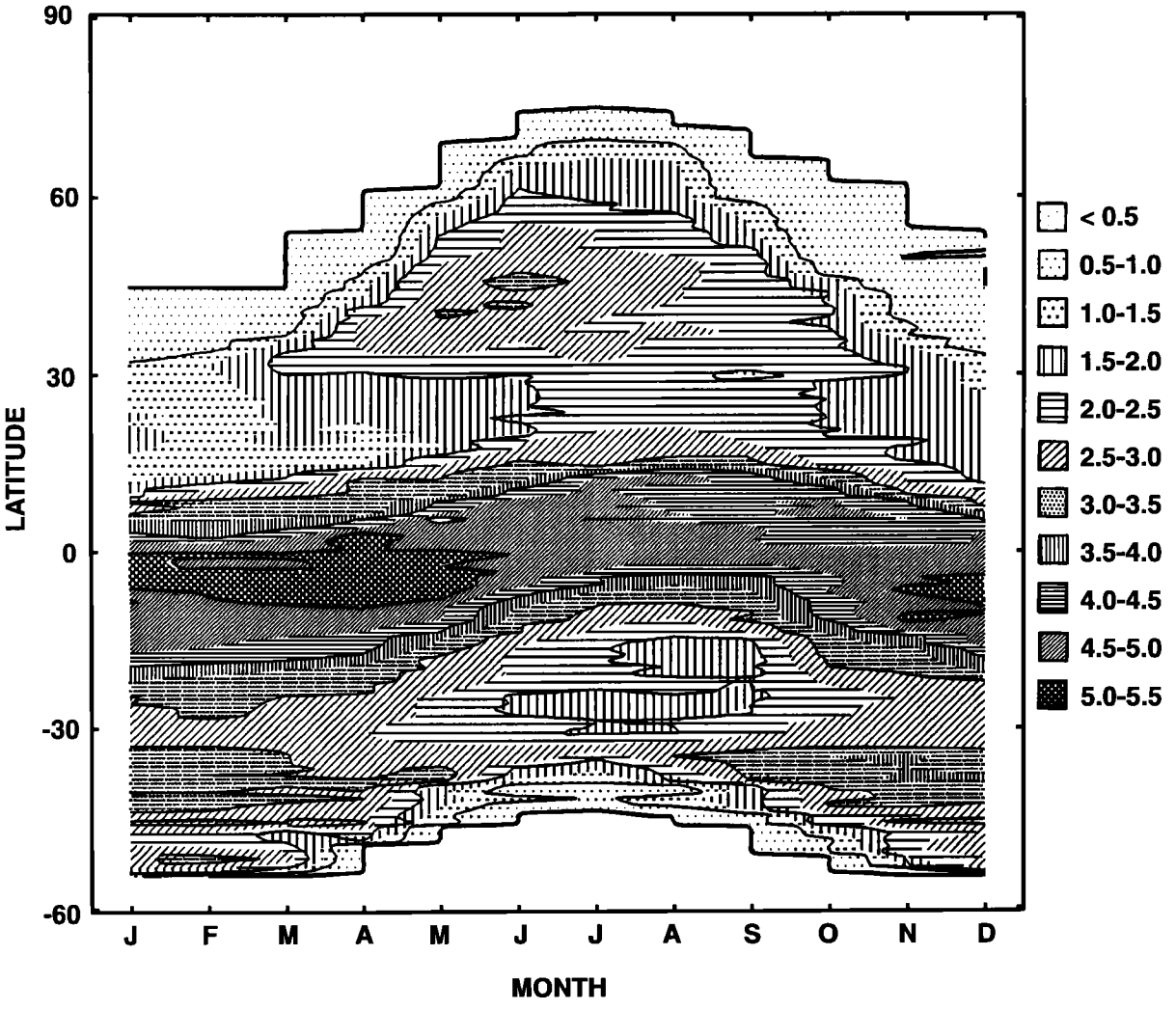

Fig. 3. Seasonal and latitudinal distribution of the N_2O production potential (N2O). The zonal means are calculated over land areas.

subtropics have the highest levels of N_2O production. Mediterranean regions have intermediate values and soils in cold temperate and boreal regions, as well as deserts, have the lowest potential for N_2O production.

The most important soil group, in terms of areal extent and nitrous oxide production, is the Ferralsols (Table 1, group 13; Table 6a, group 13A). Because of their occurrence in somewhat drier climates, Acrisols (group 11) show slightly lower N2O than do Ferralsols, while the fertile Nitosols (group 12) have higher values than Ferralsols. The extensive subtropical and tropical Luvisols (Table 6a, group 5A) also exhibit high N_2O potential. Other soils with high N2O levels, but occupying minor areas, are tropical Podzols (group 2A), Vertisols (group 16), Andosols (group 17), Fluvisols (group 19) and Gleysols (group 20). The subtropical Phaeozems and Kastanozems (groups 7A and 9A, respectively), occurring mainly in South America, exhibit high N_2O indices but their global effect is moderated by their small areas. Their temperate counterparts (Table 6b, groups 7B and 9B) show much lower N2O levels. Another soil group of significant area is the shallow Leptosols (group 21). The model predicts that temperate Leptosols, when covered by their natural forest vegetation, have very low N_2O production, while tropical Leptosols are intermediate. About 15% of the Earth's ice-free land area is covered by desert soils (group 14) which have low potential for N_2O production mainly due to precipitation limitation. Tropical organic soils (group 23) show much higher N2O values than their temperate counterparts.

Generally where N2O is low, percent standard deviations are high, although the absolute standard

deviation may be low. The low annual N2O values of temperate areas have higher percent standard deviations than do the tropics even when occupied by the same soil. Highest standard deviations are found in both tropical and temperate extents of groups 14 (desert soils), 15 (saline and alkaline soils), 18 (sand soils), 21 (shallow soils), and 22 (weakly developed soils), (Table 1, Plate 1). Percent standard deviations are small for the temperate and tropical distributions of Vertisols (group 16).

Temporal variability (not shown in Table 6) is expectedly high for temperate soil groups because of effects from seasonal temperature and moisture regimes. Very high intra-annual variabilities are also found for soils in semiarid and arid climates (soil groups 14-15) in both the tropics and temperate zones presumably due to precipitation fluctuations. N_2O indices vary seasonally for soils conditioned by parent material (groups 16-18) and for soils conditioned by their physiographic position (groups 19-22) but this variability is probably induced by the occurrence of these soils over a broad climatic range. Tropical and subtropical soils of wet climates (groups 11-13), show muted variations in N2O during the year.

Figure 3 shows the seasonality of N_2O potential modeled in this study. Expectedly, the seasonal variation is greatest for temperate climates of the northern hemisphere; the seasonal variation in temperate climates of the southern hemisphere is about half that in the north. Tropical soils are active nitrous oxide sources throughout most of the year. Moreover, monthly N2O values are higher for most of the tropics than for temperate climates; annual N2O sums can be a factor 3-4 higher in the tropics than in temperate zones. These broad-scale patterns from a simple model agree with variations in decomposition rates and amounts of carbon and nitrogen cycling through soils in tropical and temperate climates [Jenkinson and Ayanaba, 1977; Vitousek, 1984].

4.2. *Sensitivity Experiments*

Characteristics of the sensitivity experiments are briefly described in Table 7. Annual N_2O production potential for the sensitivity experiments are shown in Table 6.

Experiment 1 (- SOD). In temperate climates, this experiment yields much higher values for annual N2O than those of the reference case by removing temperature limitations in autumn, winter and spring (Table 6b). In the tropics, the experiment gives somewhat lower N2O values (e.g., Table 6a, soil groups 12A and 13A) than the reference case. The role of SOD is also expressed by differences in the variability between the reference case and experiment 1. The spatial variability as expressed by the percent standard deviation decreases considerably for most extratropical soils when SOD is excluded (except for the semiarid Kastanozems and desert soils - Table 6b, groups 9B and 14B, respectively). For most tropical soil groups, the percent standard deviation is higher in experiment 1 than in the reference case.

Experiment 2 (- CARBON). For nearly all tropical and temperate soils, this experiment yields N2O values lower than those of the reference case. Results differ from the reference case most markedly in the wet tropics and subtropics, particularly for the Ferralsols (group 13). Over the distribution of these soils, exclusion of CARBON causes an average decline of 5 in the annual mean N_2O potential. In this experiment higher N2O values are calculated for temperate soil groups 8B and 9B (steppe soils), 14B and 15B (desert soils) and for some minor tropical soil groups (15A, 16A, and 22A). The effect of excluding CARBON is minor in semiarid, arid, and steppe areas because other factors limit N_2O production. In the desert soils (group 14) and temperate steppe soils, N2O is low in both the reference case and experiment 2 due to moisture limitations.

The results of experiments 1 and 2 indicate that SOD and CARBON are driving N_2O production in wet and moist tropics. Input of organic matter plays a less important role in temperate climates, because the annual N2O is primarily determined by low temperatures in winter; and in dry climates, where soil moisture is the major regulator. These observations agree with the suggestion that carbon nowhere really prevents denitrification [Tiedje, 1988].

Excluding CARBON decreases the spatial variability for most temperate and tropical soil groups conditioned by their parent material (soil groups 15-18), but has no major effect on the variability in tropical soils in wet climates (Table 6a, groups 11A-13A). Exclusion of CARBON decreases the variability over tropical shallow soils (group 21A), whereas the variability increases for temperate zone distributions of these soils (group 21B). In the major climate-conditioned temperate soils (groups 3B-9B) exclusion of the organic input lowers spatial variability.

Experiment 3 (- FERT). Exclusion of soil fertility strongly reduces the annual N2O for most highly fertile soils in temperate and tropical zones, for example, the Phaeozems, Chernozems, Kastanozems, and Nitosols (groups 7, 8, 9 and 12, respectively) and increases N2O for the infertile tropical soils (group 2A, 3A, 13A, 15A, 18A, and 23A in Table 6a). For other temperate and tropical soils with intermediate soil fertility, the effect of experiment 3 is minor. Excluding soil fertility increases the standard deviation for most temperate and tropical soil groups due to the simplicity of the fertility scale in which the same index is associated with most soil units within each group. However, within landscapes, soil fertility may be a major cause

TABLE 7. List of Experiments to Evaluate the Sensitivity of the N_2O Production Index to Different Controls

Experiment	Description
Reference case:	all 5 factors are used; SOD1 is from Mosier and Parton [1985]
	$N2O = \sum_{1}^{y}(O2)^{1/5} \times (H2O)^{1/5} \times (SOD)^{1/5} \times (FERT^*)^{1/5} \times (CARBON)^{1/5}$
Experiment 1 (- SOD)	as reference case, but SOD is excluded
	$N2O = \sum_{1}^{y}(O2)^{1/4} \times (H2O)^{1/4} \times (FERT^*)^{1/4} \times (CARBON)^{1/4}$
Experiment 2 (- CARBON)	as reference case, but CARBON is excluded
	$N2O = \sum_{1}^{y}(O2)^{1/4} \times (H2O)^{1/4} \times (SOD)^{1/4} \times (FERT^*)^{1/4}$
Experiment 3 (- FERT)	as reference case, but FERT* is excluded
	$N2O = \sum_{1}^{y}(O2)^{1/4} \times (H2O)^{1/4} \times (SOD)^{1/4} \times (CARBON)^{1/4}$
Experiment 4 (- O2)	as reference case, but O2 is excluded
	$N2O = \sum_{1}^{y}(H2O)^{1/4} \times (SOD)^{1/4} \times (FERT^*)^{1/4} \times (CARBON)^{1/4}$
Experiment 5 (- soil variability)	as reference case, but CARBON is excluded and the soil parameters are equal for all soils: FERT = 3, DRNG =1, and texture is fine. This experiment studies the effect of climate on the variability of N2O
	$N2O = \sum_{1}^{y}(O2)^{1/4} \times (H2O)^{1/4} \times (SOD)^{1/4} \times (FERT^*)^{1/4}$
Experiment 6 (H2O and O2 of current month only)	as reference case, but soil-water and oxygen status in the preceding month is not considered. H2O and O2 are the diagonals of Table 4 and 5, respectively.
Experiment 7 (only CARBON)	CARBON is used to predict N2O
	$N2O = \sum_{1}^{y}(CARBON)$

FERT* = 2 × FERT, the fertility index from Table 1. See text for explanation.

of variability in N_2O fluxes [Table 8; Livingston et al, 1988; Matson et al. 1990].

Experiment 4 (- O2). The O2 factor provides information not included in the other four factors over the whole range of temperate and tropical ecosystems. Under wet conditions, high O2 raises the levels of expected denitrification. Similar conditions produce low H2O values simulating blockage of nitrification. Hence, because of the partial overlap of the scales of O2 and H2O, important effects on overall levels of N2O in this experiment are found only in well-drained soils. No effect, or a decrease relative to the reference case, is found for the poorly-drained Gleysols and Histosols (soil groups 20 and 23, respectively). Where aerobic conditions prevail, O2 depresses the N_2O index (Table 5). In most tropical and temperate soils, annual N2O calculated in experiment 4 is higher and variability is lower than in the reference case, in agreement with Tiedje [1988], who concluded that in aerobic systems, oxygen is the principal factor limiting denitrification.

Experiment 5 (- soil variability - CARBON). In experiment 5, CARBON is excluded and for all soils FERT = 3, DRNG = 1 (well drained) and texture is fine (high soil-water storage capacity). This eliminates variability produced by soil and vegetation differences and isolates the spatial variability caused by climate. The results can best be compared with experiment 2 (- CARBON). Smoothing soil differences increases spatial standard deviations for about half of the temperate soil types (Table 6b, groups 3B, 7B, 8B, 11-13B, 15-17B, 20B) and for most tropical soil groups (Table 6a). Tropical soils showing lower variability in this experiment are groups 12A-14A and 21A-23A. What this means can best be illustrated for the Ferralsols (group 13A), the major tropical soil group. These soils occur in relatively uniform climates so soil differences contribute to the variability. The

TABLE 8. Summary of Measurements of Nitrous Oxide Fluxes From Natural Ecosystems and the Corresponding Site Information

Vegetation Type/Ecosystem	Pa	Ta	Soil Texture	DC	pH	Nitrification, μg N/d/g soil	Flux μg N $m^{-2}h^{-1}$ Range	Flux μg N $m^{-2}h^{-1}$ Mean	Month of Measurement	Soil Information and Location; Where Known, FAO/Unesco [1974-1981] and USDA [1975] classifications are given (USDA in parentheses)	Ref.[a]
Temperate Regions, Nonwetland Sites											
Grasslands											
Native shortgrass prairie	300		fine loamy	wd[b]				9.6	5-9	Xerosol (ustollic Haplargid), Colorado	1[c]
Native shortgrass prairie	300		15% clay (slope)	wd[b]				0.9	1 y	Xerosol (ustollic Haplargid), slope, Colorado	2[c]
Native shortgrass prairie	300		28% clay (bottom)	wd[b]				1.8	1 y	Kastanozem (aridic Argiustoll), swale, Colorado	2[c]
Grass			loam	wd[b]			0.5-2.5	1.5	>1 y	loess soil, Mainz, Germany	3
Native prairie	232[d]		loamy sand	wd[b]	6.7		0.4-1.8	0.7[b]	9-3	Wisconsin	4[c]
Prairie	232[d]		sand	wd[b]	6.2		0.4-2.1	0.5[b]	9-3	Arenosol (typic Udipsamment), Wisconsin	4
Prairie	274[d]		silt loam	wd[b]	7.3		0.4-3.2	0.7[b]	9-3	lithic Chernozem (lithic Haplustoll), Wisconsin	4[c]
Tall grass prairie, burned	600-800[b]	10[b]			6.0		2.2, 2.2[e]		6-10, 4-10	loess over glacial till, Wisconsin	5
Tall grass prairie	600-800[b]	10[b]			6.0		2.5, 2.2[e]		6-10, 4-10	loess over glacial till, Wisconsin	5[c]
Grass (meadow)			sand				2.0-13.0		>1 y	Mainz, Germany	3
Grass (wet meadow)	600-800[b]	10[b]		pd[b]	6.1		30.6, 30.6[e]		6-10, 4-10	Wisconsin	5
Deciduous forests											
Mixed forest				wd[b]			1.0-3.0		>1 y	loess soil, Mainz, Germany	3[c]
Deciduous forest	900[b]	13[b]						10.3	1 y	mineral soil, New York	6
Hardwood forest	1300	6-13[d]				13 kg $ha^{-1}y^{-1}$		2	summer	soils in glacial till, New Hampshire	7
Oak			sandy loam	wd[b]	3.7[f]		4.5-10.5[g]	8.5	1 y	brown sandy soil, 7.2% C, Mainz, Germany	8
Oak			sandy loam	wd[b]	3.6[f]		3.5-9.5[g]	7.8	1 y	Podzol (Spodosol), 1-3 cm litter, 2.8% C, Mainz, Germany	8
Oak-hornbeam			sandy loam	wd[b]	3.7[f]		5.5-7.5[g]	7.7	1 y	Podzol (Spodosol), 1-2 cm litter, 2.4% C, Mainz, Germany	8

TABLE 8. (continued)

Vegetation Type/Ecosystem	Pa	Ta	Soil Texture	DC	pH	Nitrification, μg N/d/g soil	Flux μg N $m^{-2}h^{-1}$ Range	Flux μg N $m^{-2}h^{-1}$ Mean	Month of Measurement	Soil Information and Location; Where Known, FAO/Unesco [1974-1981] and USDA [1975] classifications are given (USDA in parentheses)	Ref.[a]
Oak-hornbeam			sandy loam	pd[b]	3.4[f]		5.5-7.5[g]	10.6	1 y	pseudogley, 1-3 cm litter, 3.4% C, Mainz, Germany	8
Hornbeam-oak			sandy loam	wd[b]	4.7[f]		1.5-3.5[g]	3.0	1 y	eutric Cambisol (typic Dystrochrept), 2.8% C, Mainz, Germany	8[c]
Hornbeam-oak			sandy clay loam	wd[b]	6.7[f]		2.5-4.5[g]	3.8	1 y	eutric/dystric Cambisol (typic/dystric Eutrochrept), 3.6% C, Mainz, Germany	8[c]
Black oak					5.0		5.4, 15.5[e]		6-10, 4-10	Wisconsin	5[c]
Black oak, 80 y			sandy loam	wd	sl. acid[b]		-0.01-0.56	0.27	1 y	Podzol/Cambisol (entic Haplorthod), stony, 5.2-7.8 cm litter, Mass.	9[c]
Coniferous forests											
Red pine, 62 y			sandy loam	wd	sl. acid[b]		-0.08-0.42	0.17	1 y	Podzol/Cambisol (entic Haplorthod), stony, 4.3-4.9 cm litter, Mass.	9
White pine, 40 y	600-800[b]	10[b]			4.5		27.7, 36.4[e]		6-10, 4-10	Wisconsin	5
Temperate Regions, Wetland Sites											
Forest, organic soil			organic	pd				11.4	1 y	Florida Everglades	6[c]
Marsh (sedge meadow)			organic	pd	7.0		0.7, 1.1[e]		6-10, 4-10	Wisconsin	5
Salt marsh (sp. alterniflora)			organic	pd				3.5	1 y	Louisiana	10[c]
Brackish marsh (sp. patens)			organic	pd				5.4	1 y	Louisiana	10[c]
Fresh marsh (Panicum hemitomon)			organic	pd				6.3	1 y	Louisiana	10[c]
Open water, salt								1.1	1 y	Louisiana	10
Open water, brackish								2.4	1 y	Louisiana	10
Open water, fresh								3.9	1 y	Louisiana	10
Marsh, drained	600-800[b]	10[b]	organic	wd	6.1		64.8, 148.7[e]		6-10, 4-10	Wisconsin	5

TABLE 8. (continued)

Vegetation Type/Ecosystem	Pa	Ta	Soil Texture	DC	pH	Nitrification, μg N/d/g soil	Flux μg N $m^{-2}h^{-1}$ Range	Flux μg N $m^{-2}h^{-1}$ Mean	Month of Measurement	Soil Information and Location; Where Known, FAO/Unesco [1974-1981] and USDA [1975] classifications are given (USDA in parentheses)	Ref.[a]
Tropical Regions, Nonwetland Sites											
Savannas											
Savanna (grassland/woodland)	1000	15-20[b]	sandy loam/sand	wd[b]	<6[f]		2.0-6.4	4	2	dry season, Venezuela	11[eh]
Savanna (grassland/woodland)	1000	15-20[b]	sandy loam/sand	wd[b]	<6[f]			17	2	watered soil, Venezuela	11[eh]
Undisturbed forests											
Terra firme moist forest	2000	25.8		wd[b]				43	4	Ferralsol (Oxisol), Manaus, Brazil	7[c]
Terra firme moist forest	2000	25		wd[b]				13	12	Ferralsol (Oxisol), Manaus, Brazil	12[c]
Terra firme moist forest	2000	24		wd[b]				31	3	Ferralsol (Oxisol), Manaus, Brazil	12[c]
Primary tropical moist forest	4300	22		wd[b]				8	7	Tena, Ecuador	12[c]
Elfin cloud forest		19		wd[b]				11	4	Puerto Rico	12[c]
Colorado/Palm forest		20		pd				3	4	Puerto Rico	12
Primary forest	4100	25				0.16-2.14	29-52	40	10	Old alluvial, La Selva, Costa Rica	13[c]
Primary forest	4100	25				0.14-2.10	7-25	16	10	Old alluvial, La Selva, Costa Rica	13[c]
Primary forest	4100	25				1.42-2.16	14-32	23	10	Soils formed in basalt, La Selva, Costa Rica	13[c]
Primary forest	4100	25				1.37-1.67	41-83	62	10	Soils formed in basalt, La Selva, Costa Rica	13[c]
Primary forest	4100	25				2.44-3.62	12-24	18	10	Soils formed in basalt, La Selva, Costa Rica	13[c]
Primary forest	4100	25				2.21-2.73	37-61	49	10	Soils formed in basalt, La Selva, Costa Rica	13[c]
Primary forest, 75 y	2700	22		wd[b]		1.88-24.6	9-43	26	7	Andosol (Andept), Turrialba, Costa Rica	13[c]

TABLE 8. (continued)

Vegetation Type/Ecosystem	Pa	Ta	Soil Texture	DC	pH	Nitrification, μg N/d/g soil	Flux μg N $m^{-2}h^{-1}$ Range	Flux μg N $m^{-2}h^{-1}$ Mean	Month of Measure-ment	Soil Information and Location; Where Known, FAO/Unesco [1974-1981] and USDA [1975] classifications are given (USDA in parentheses)	Ref.[a]
Lowland forest, undisturbed	2200	25		wd[b]			15-35		1 y	Ferralsol (Oxisol), Manaus, Brazil	14[c]
Terra firme forest	1770	26	clay	wd[b]	4.0	1.88-2.44	9.4-12.6	11.0	8	ridge, Ferralsol/Acrisol (Oxisol/Ultisol), Amazonia, Brazil	15[c]
Terra firme forest	1770	26	clay	wd[b]	4.0	1.42-1.66	8.7-13.3	11.0	8	slope, Ferralsol/Acrisol (Oxisol/Ultisol), Amazonia, Brazil	15[c]
Campinarana forest	1770	26	sand[b]	pd[b]	3.7	0.49-0.73	8.3-11.7	10.0	8	valley, Podzol/Arenosol (Spodosol/Psamment), Amazonia, Brazil	15
Terra firme forest	2200	25	clay	wd[b]		1.02-1.20		19	4-5	Ferralsol (Oxisol), Manaus, Brazil	16[c]
Terra firme forest	2200	25	sand	wd[b]		0.05-0.09		3	4-5	Arenosol (Psamment), Manaus, Brazil	16
Primary montane forest	2200	16		wd[b]		-0.04		0	1	Andosol (Andept), 200 y, Hawaii	13
Primary montane forest	2200	16		wd[b]		-0.04	0.4-2.0	1.2	1	Andosol (Andept), 200 y, Hawaii	13
Primary montane forest	3500	16		wd[b]		0.06-0.18	0.5-1.7	1.1	1	Andosol (Andept), 1000 y, Hawaii	13
Primary montane forest	3500	16		wd[b]		-0.04-0.1	1.3-3.9	2.6	1	Andosol (Andept), 1000 y, Hawaii	13
Primary montane forest	4500	16		wd[b]		-0.11-1.07	1.0-2.6	1.8	1	Andosol (Andept), 4000 y, Hawaii	13
Secondary forest, logged	2000	26		wd[b]				23.1	7-8	Ferralsol (Oxisol), Manaus, Brazil	18[c]
Dry tropical forest	748	25		wd[b]				9.1	9	Cambisol (Entisol), Chamela, Mexico	17[c]
Dry tropical forest	748	25		wd[b]				2.0	3	Cambisol (Entisol), Chamela, Mexico	17[c]

TABLE 8. (continued)

Vegetation Type/Ecosystem	Pa	Ta	Soil Texture	DC	pH	Nitrification, μg N/d/g soil	Flux μg N $m^{-2}h^{-1}$ Range	Flux μg N $m^{-2}h^{-1}$ Mean	Month of Measurement	Soil Information and Location; Where Known, FAO/Unesco [1974-1981] and USDA [1975] classifications are given (USDA in parentheses)	Ref.[a]
Disturbed forests											
Secondary forest, 20 y	4200	25				1.92-2.56	4-52	28	10	Recent alluvial, La Selva, Costa Rica	13
Secondary tropical moist forest		22		wd[b]				7.4	7	Ecuador	12
Tabanuco forest, secondary		23		wd				42.5	4	Acrisol (Ultisol), Puerto Rico	12
Mahogony plantation		30		wd[b]				7.9	4	Puerto Rico	12
Lowland forest, cleared, burned	2200			wd[b]			15-35		1 y	Ferralsol (Oxisol), Manaus, Brazil	14
Tropical Regions, Wetland Sites											
Varzea	2200	25		pd			0.26-0.34	1	4-5	waterlogged, Gleysol (?), Manaus, Brazil	16[c]

Pa= mean annual precipitation (mm); Ta= mean annual temperature (°C); DC = drainage class; wd = well drained; pd = poorly drained.

[a] 1, Mosier et al. [1981]; 2, Parton et al. [1988]; 3, Seiler and Conrad [1981]; 4, Cates and Keeney [1987]; 5, Goodroad and Keeney [1984a]; 6, Duxbury et al. [1982]; 7, Keller et al. [1983]; 8, Schmidt et al. [1988]; 9, Bowden et al. [1990]; 10, Smith et al. [1983]; 11, Hao et al. [1988]; 12, Keller et al. [1986]; 13, Matson and Vitousek [1987]; 14, Luizao et al. [1989]; 15, Livingston et al. [1988]; 16, Matson et al. [1990]; 17, Vitousek et al. [1990]; 18, Keller et al. [1988].

[b] Interpretations: A. F. Bouwman.

[c] Measurements used in the comparison with modeled N2O.

[d] During measurements.

[e] First value refers to summer/autumn 1979; second value to summer/autumn 1980; no annual figures available.

[f] Soil pH measured in KCl solution.

[g] 50% probability with 95% confidence range.

[h] For the dry season, measurement data were compared with the modeled N2O value averaged for May-October; for the rainy season, measurement data for the watered soil were compared with the modeled N2O values averaged for November-May.

high spatial variability within soil groups 15A-B to 22A-B, soils conditioned by factors other than climate, reflects the distribution of these soils over different climatic zones. As in the reference case and experiment 1, the percent standard deviation among temperate soil groups is higher than in most of the equivalent tropical soils.

Experiment 6 (not considering soil water and oxygen of the previous month). Effects of wetting and drying are excluded in this experiment; H2O and O2 indices are given by the diagonals in Tables 4 and 5, respectively. The overall effect of considering water status only of the current month is minor and effects do not show patterns specific to soil groups or clusters. However, seasonal N2O patterns exhibit a response. Results for selected sites (section 4.3) illustrate cases in which monthly N_2O indices are equal to those of the reference case (e.g., the Brazilian site). However, in sites with marked seasonality of rainfall, experiment 6 exhibits lower N2O values at the onset of the wet season and higher values at the end of the growing period. The net result is no, or only minor, differences in the annual sum. For most soil groups conditioned by climate, spatial variability declines slightly in temperate regions (Table 6b, groups 2B, 5B, 7B, 9B, 10B, 12B-14B) and increases in the tropics (Table 6a).

Experiment 7 (only CARBON). Using CARBON as the sole predictor of N_2O production generally yields higher values than the reference case. Exceptions are tropical desert soils, Vertisols and Regosols (groups 14A, 16A, and 22A, respectively). N2O increases are largest in temperate soils and in soils of the wet tropics. Standard deviations in experiment 7 are generally elevated for the tropical soils. Among temperate soil groups, variability is both higher and lower than in the reference case suggesting no clear relation with climate.

The CARBON factor represents organic matter inputs and not N inputs. In addition, CARBON includes much but not all information needed to characterize conditions responsible for N_2O production. In particular, soil aeration (drainage and soil wetness), soil-water availability, and possibly soil fertility, are probably not captured by the NDVI. Another problem of the underlying NDVI data is that NPP is overestimated in a number of ecosystems, particularly needleleaved forests and vegetation types with a strong seasonal pattern in growth [Box et al., 1989]. The broad spatial patterns and overall levels of CARBON are, however, very similar to the distribution of N2O values from the reference case.

4.3. *Results for Selected Sites*

We selected four sites to discuss more fully. They are distributed throughout a range of climatic and ecological regimes and include locations representative of globally important soil groups, as well as regimes dominated by various factors in the model, for example, water balance, temperature, soil fertility. One site represents a semiarid temperate climate, the second a humid temperate site, and two tropical sites include a seasonal climate and a per-humid climate. In the following discussions, the three functions describing soil organic matter decomposition (SOD) discussed above are referred to in abbreviated form as follows: SOD1, Mosier [from Mosier and Parton, 1985; Parton et al., 1988]; SOD2, Parton [from Parton et al., 1987]; SOD3, Fung [from Fung et al., 1987]. The base or reference case is the Mosier function, SOD1 (Figure 2).

Colorado, Temperate Arid North America. The first site a semiarid grassland region in Colorado in the western US (Figure 4a) occupied by shortgrass prairie with no woody cover. The rescaled NDVI sum representing carbon supply is only 3.4 which lies in the low end of the scale for this index, consistent with the low biomass semiarid ecosystem. The underlying soil, a luvic Kastanozem, is a highly fertile soil conditioned by steppe climates (Table 1) and occurs here under conditions of about 350-mm annual precipitation which is exceeded by potential evapotranspiration (about 630 mm per year). The continental location results in mean monthly temperatures that vary within a few degrees of 0°C for five months of the year and rise to the low twenties in July and August, increasing the potential production of N_2O. However, in this summer period, moisture deficits control the ecosystem due to consistently low precipitation. Soil-water deficits are extreme for the entire second half of the year, resulting in reduced O2 and H2O (denitrification and nitrification, respectively) factors for most of the year. Organic matter decomposition (SOD) is moderate at this site although the three SOD functions vary considerably. The lowest is from the Mosier curve (SOD1 = 16) followed by 25 and 33 from SOD3 and SOD2, respectively.

The annual N_2O production for the base case is low, depressed by several factors that act serially during the year. N_2O production shuts down from November through April due to low temperatures; warm summer temperatures, dovetailing with moderate rainfall, create dry well-aerated soils. As a result, the seasonal pattern of N2O is governed by elevated O2 (denitrification) and H2O (nitrification) indices in conjunction with low rates of decomposition in the spring, followed by trend reversals in these three factors in the summer.

Excluding the fertility factor (experiment 3) lowers N2O from 17 to 12, an expected response since the luvic Kastanozems here are associated with the maximum fertility index. Experiment 5 results in a similar decline in N2O for similar reasons: the annually constant fertility parameter is reset to a middle value and the effect of organic matter availability is removed. As an attempt to focus on the climate effect, experiment 5 reflects observations

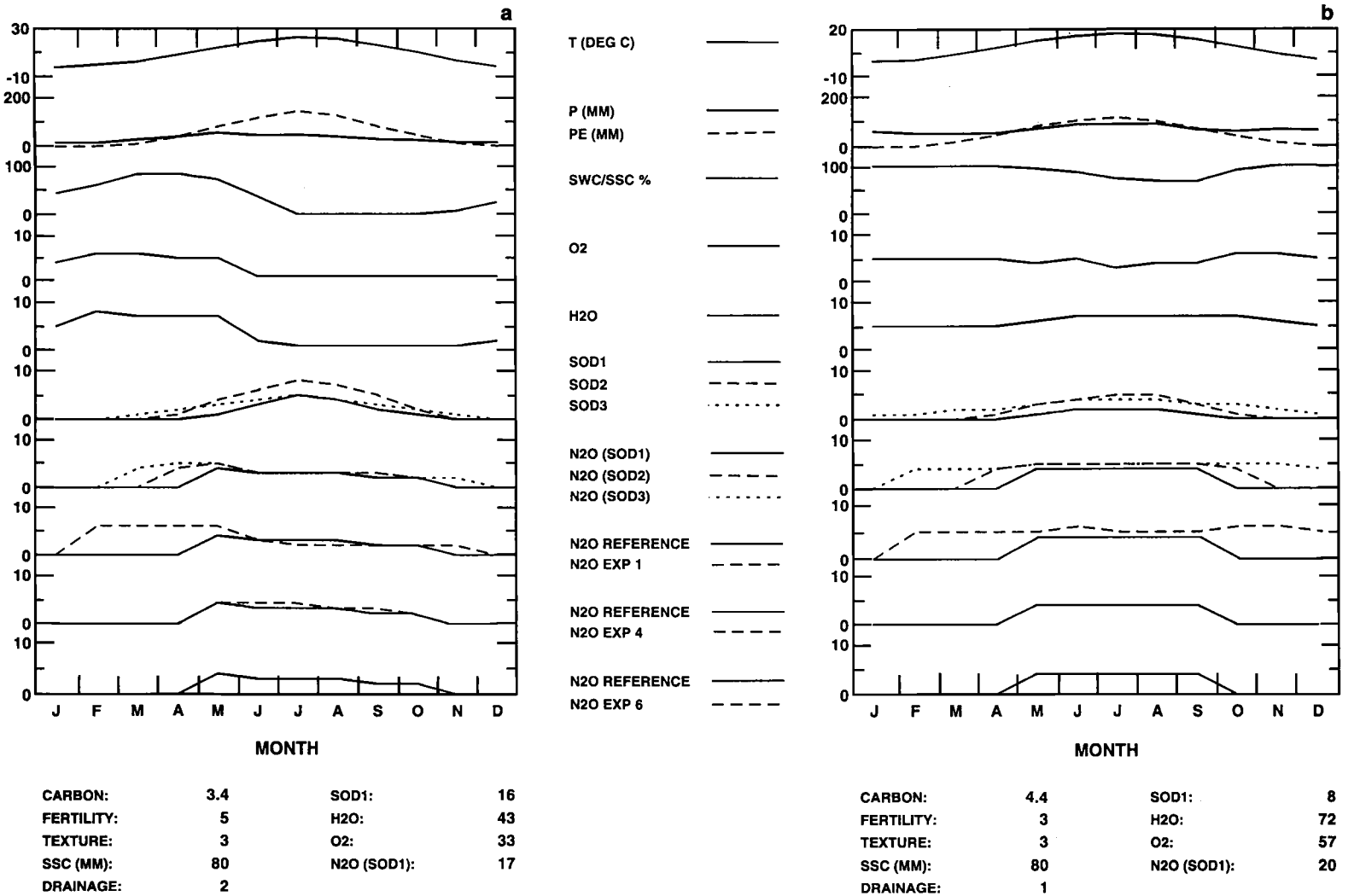

Fig. 4. Environmental characteristics, control indices, and N_2O production indices at four sites: (a) Colorado, temperate arid North America, (b) Germany, temperate western Europe, (c) Venezuela, tropical seasonal South America, and (d) Brazil, tropical humid South America. The three modeled N_2O indices are derived from the three decomposition functions shown in Fig. 2; SOD1 is used in the reference case.

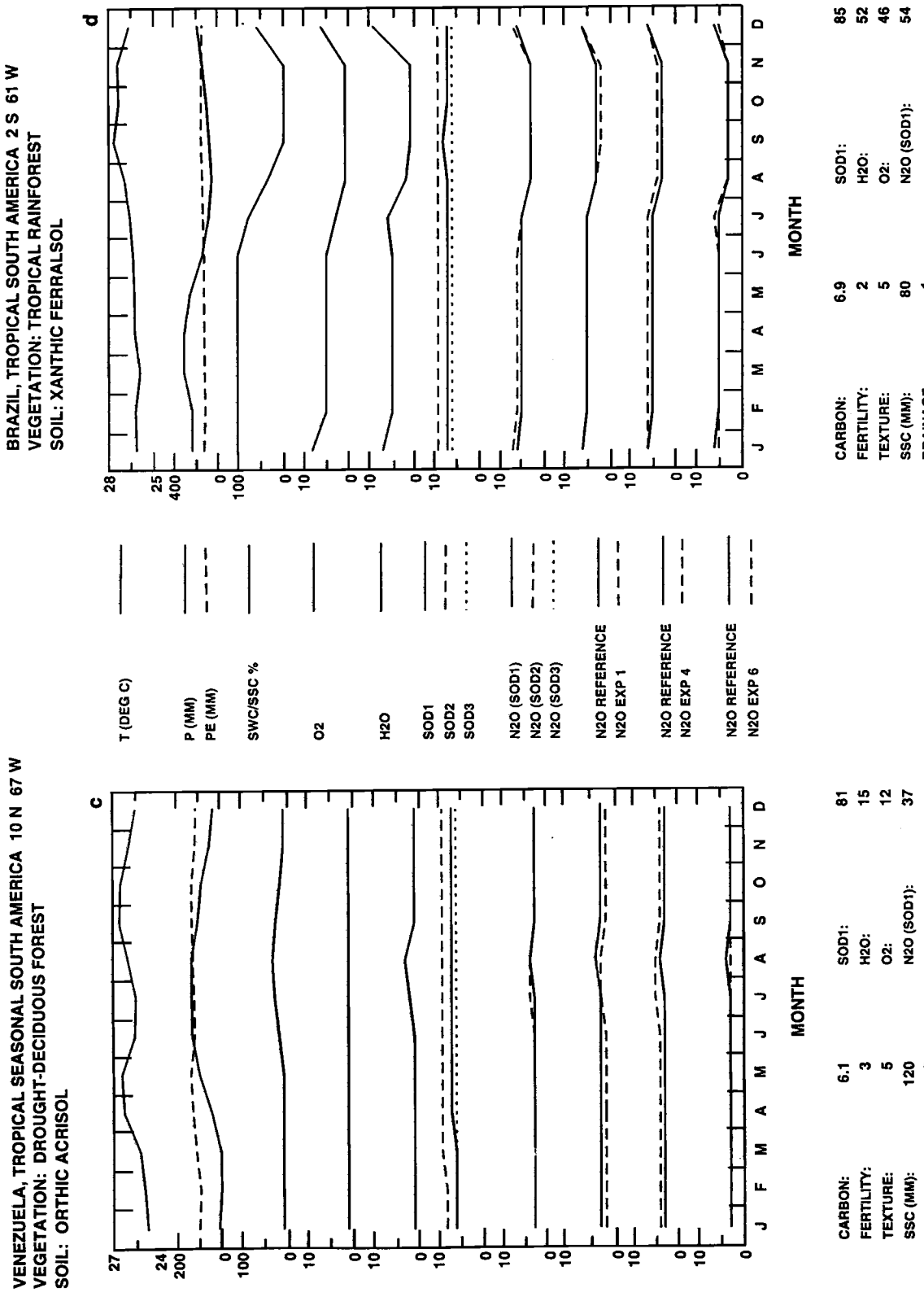

Fig. 4. (Continued).

indicating that seasonal and relatively arid temperate climates carry inherently low potential for N_2O production. Experiments 2 and 4 exhibit moderate divergence from the base case with slight increases in the annual N2O value but little seasonal redistribution indicating that the factors evaluated in these experiments (carbon availability, oxygen limitation and soil-water history) exert approximately equal control over N2O modeled at this site.

The highest N2O value is for experiment 1 since seasonal temperature limitations on the decomposition of soil organic matter are relaxed in this experiment. In the reference case, monthly N2O values are zero from November through April, and range between 4 and 2 during the productive season of May to October; in experiment 1, N_2O production rises as high as 6 and remains elevated for a long season lasting from February to November. Overall, N_2O production in this semiarid temperate environment appears to be limited by low water availability and low organic matter input.

Overall N_2O production in this semiarid temperate enviorment appears limited by high aerobicity, low water availability and low carbon supply which are not sufficiently counteracted by the high summer temperatures.

Germany, Temperate Western Europe. The site in western Germany is in a region of temperate deciduous forest admixed with evergreens (Figure 4b). CARBON is intermediate at 4.4; the underlying soil belongs to the dystric Cambisol group, moderately fertile soils with weak profile development, free drainage and good aeration (Table 1). The site is located in a cool wet climate characterized by a surplus of precipitation over potential evapotranspiration (820 mm and 594 mm per annum, respectively).

Organic matter decomposition at this site varies by a factor of four among the three functions; the lowest was for SOD1 (8), followed by SOD2 and SOD3 (30). SOD1 predicts low decomposition rates during a short season from May to September while SOD2 gives higher, slightly peaked, values in summer when temperatures are in the 10°-20°C range, where largest differences are expected. For the SOD3 relationship, temperature exerts weaker control on the level and duration of decomposition, resulting in relatively low and constant decomposition throughout the year. Annual N2O estimated via the three relationships exhibits patterns similar in seasonality to their respective SOD factors and to the overall trend in temperature and H2O; they range from the base case of 20 (SOD1) to 33 (SOD2) and 51 (SOD3). Although the predicted N2O level is similar among the three relationships for months when they all indicate N_2O activity, the productive seasons are longer by several months with the SOD2 and SOD3 relationships.

The sensitivity experiments generally produced minimal variations on the seasonal and total values of N2O indicating that most parameters play equal roles in annual N2O estimates at this site, as well as reflecting the temporally constant status of water and oxygen parameters. The only major effect, increasing N2O to about 2.5 times that of the base case, is in experiment 1 which virtually eliminates the seasonal low-temperature limitation on decomposition and N mineralization; N2O levels for individual months in experiment 1 are somewhat higher than those for the reference case and rise above zero for a long season extending from February through December in contrast to the five-month productive season for the base case. Since the system is well supplied with moisture throughout the year, soil-water history is not a crucial factor in the production of N_2O (experiment 6).

The results of the reference case and sensitivity experiments indicate that N_2O production in fertile, humid forest zones in moderate climates is controlled predominantly by temperature. Moisture-related parameters exert little limitation except that the relative constancy of moist soil conditions throughout the year, while contributing to conditions amenable to N_2O production, does not produce the high N2O pulses that accompany the wetting of dry soils.

Venezuela, Tropical Seasonal South America. The South American site is occupied by drought-deciduous forest underlain by orthic Acrisols with mildly impeded drainage characteristic of wet tropical and subtropical climates with seasonal rainfall (Figure 4c). Almost half of the ~900-mm annual precipitation falls from June to August; the drier winter months (January-March) have $\leq$ 20 mm rainfall monthly. Constant high temperatures produce small variations in potential evapotranspiration, which ranges from 100 mm in February to 143 mm in May. This relatively flat trend in PE, combined with highly seasonal precipitation, produces conditions of moisture deficit from September to May; the season of small moisture surplus is confined to June/July and precipitation following the winter aridity produces a seasonal spike in nitrification (H2O). As expected, the temperature-dependent decomposition functions are very similar and essentially constant through the year. Other site characteristics (fertility and drainage) are intermediate but the organic matter supply is elevated reflecting the higher deciduous biomass of the vegetation.

The reference N2O value is less than one half the global maximum; the alternative SOD formulations are essentially equal to the reference case, i.e., highly seasonal values mimic the H2O curve. This seasonal tropical forest site exhibits only moderate responses to the series of sensitivity experiments because of the generally neutral values of site characteristics. Although temperature is not a major controller of N_2O production in terms of seasonality,

constant high temperatures throughout the year result in rapid decomposition so that the exclusion of SOD (experiment 1) produces a decline of ~30% in modeled N2O. For reasons mentioned above, removal of parameters seasonally constant for the site (CARBON, FERT and a combination of CARBON and soil factors) all depress the N2O values slightly. The exclusion of the O2 denitrification parameter (experiment 4), which mildly limits overall N_2O production here, produces the only increase in N_2O potential among the sensitivity experiments.

Under conditions of sufficient organic matter, efficiently delivered via fertile soils, the major features controlling the monthly and annual production of nitrous oxide in the tropical seasonal forest appear to be moisture conditions, reflected here in O2 (denitrification) and H2O (nitrification) parameters.

Brazil, Tropical South America. The Brazilian site is situated near Manaus (Figure 4d). Low fertility xanthic ferralsols are under tropical rain forest, an association common in the humid tropics. Organic matter input is high, indicated by the CARBON factor close to 7. The narrow range of annual temperatures is mirrored in the three equally constant functions describing organic matter decomposition. The reference SOD function of Mosier is intermediate at 85, while SOD2 is about 25% higher and SOD3 about 15% lower. Total precipitation is very high at about 2200 mm/year, exceeding the PE of 1675 mm/year. The constancy in temperature produces comparatively constant PE in the range of about 120-150 mm/month; although there are no very arid months, precipitation peaks at 225-300 mm/month from January to May and declines slowly to a low of 64 mm in August. Because the water storage capacity is relatively high and some precipitation continues during the dry season, the soil remains moist much of the year. More aerobic conditions in the soil are reflected in lower values of the O2 (denitrification) and H2O (nitrification) parameters for September through November. Increased soil aeration precedes declining anaerobicity by a month. Annual N2O values from the three temperature functions are very similar; Mosier (SOD1) and Fung (SOD3) are both 54 while Parton (SOD2) is higher at 61, consistent with differences expected in this temperature range (Figure 2).

Experiments 1, 2 and 6 result in N2O values slightly below the reference case. Excluding the factors accounting for organic matter input (CARBON) and decomposition (SOD), removes features that contribute to high N_2O production. Experiment 6, which evaluates the effect of the preceding month's soil water on N2O, shows slightly lower values only for the first half of the year. The remaining experiments all increase N2O estimates in this tropical site, by larger values than the declines of the other experiments: removal of the (low) fertility factor increases the annual total by about 12%; the same increase is produced in experiment 5 in which the low fertility of 2 is prescribed at 3 and the CARBON factor is excluded. The largest response, an increase of ~20%, comes from experiment 4 in which the role of denitrification was excluded. Although this location has considerable organic matter turnover, it has low fertility well-drained soils characteristic of tropical forest regions. Furthermore, the high annual precipitation is sufficiently seasonal to reduce considerably N_2O production capability for about half the year.

4.4 *Comparison With Field Measurements*

Modeled monthly N2O is compared with measured N_2O fluxes in various natural ecosystems (Table 8). This comparison allows a general evaluation of the model and data bases in a variety of environments, as well as providing a framework for translating nondimensional N2O values into N_2O fluxes.

Several observations are excluded from the comparison because site descriptions are incomplete, or the climate, soil conditions or vegetation types from the 1° data bases corresponding to measurement locations differ from those reported. In some cases, the mean of N2O values of a surrounding pair of cells with conditions essentially identical to the measurement site is compared to the measured flux.

The reference case using the SOD1 function (Figure 5) yields the best fit to the measured fluxes (r^2 for least squares fit to a quadratic function = 0.55). SOD2 and SOD3 (not shown) result in r^2 of 0.38 and 0.24, respectively. The r^2 for quadratic fits are 0.16, 0.48, 0.55, 0.43, 0.42, 0.60, and 0.33 for experiments 1-7, respectively.

Relative to the reference case, exclusion of the temperature effect (experiment 1) causes a large reduction in r^2 from 0.55 to 0.16, a dramatic increase in N2O in temperate sites (particularly in temperate climates during autumn, winter and spring), and a moderate decline in N2O values for tropical sites. In temperate summers with sufficient soil moisture, however, temperatures may be comparable with or even higher than those in the tropics. Hence, the effect of excluding SOD in summer is less important than in temperate winters.

As shown in section 4.2, the factor CARBON provides additional variability within climatic and soil regions. However, for the measurement sites considered, the exclusion of CARBON (experiment 2) reduces r^2 from 0.55 in the reference case to 0.48. Using only CARBON to predict N_2O production (experiment 7) gives r^2 of 0.33 and a large increase in N2O particularly in temperate ecosystems.

Although soil fertility may be the principal cause of variation in N_2O fluxes regionally, exclusion of soil-fertility variations globally (experiment 3) has

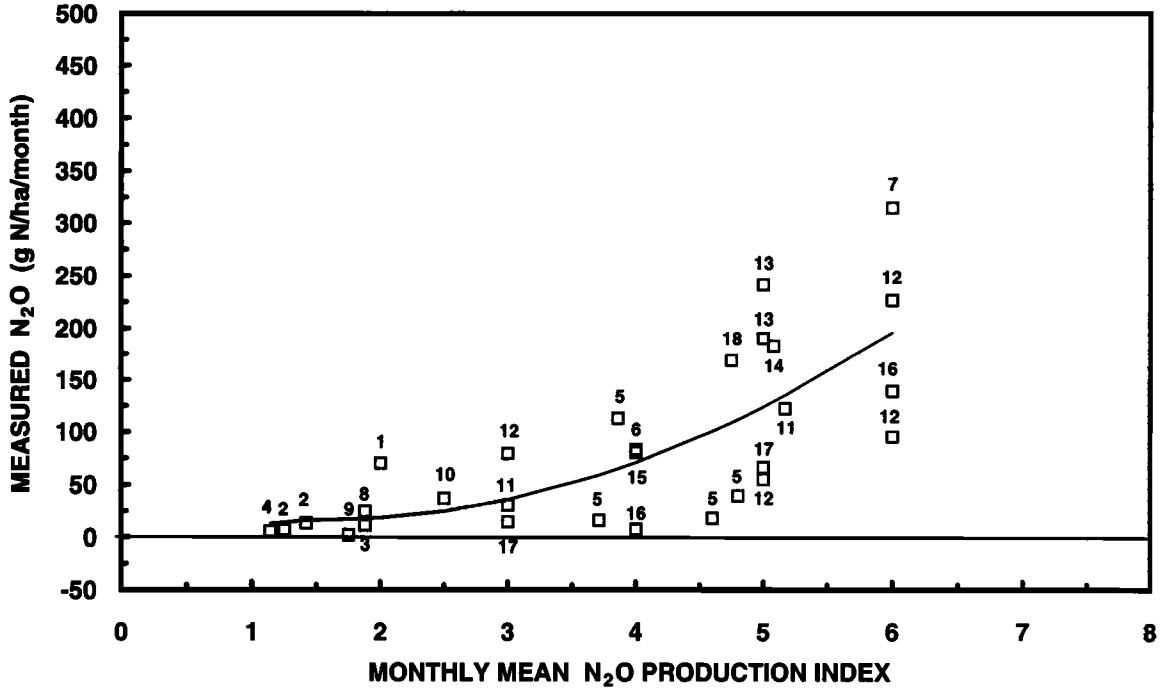

Fig. 5. Relationship between measured N_2O fluxes and modeled N2O from the reference case for a series of field sites. Labels refer to sites listed in Table 8. The solid line represents the best quadratic fit: for N2O > 1.5, flux = 9.01 × $(N2O)^2$ - 27.87 × (N2O) + 38.22; for N2O ≤ 1.5, flux = 11.13 × (N2O).

no major effect on the comparison except at temperate sites with high soil fertility (e.g., sites 1 and 2 in Figure 5). Experiment 3 suggests that the soil fertility scale used here does not resolve sufficiently the fertility variations found in natural conditions.

Excluding the oxygen limitation of soils (experiment 4) results in a value for r^2 of 0.43. Globally uniform soil texture, drainage and fertility (experiment 5) reduces r^2 from 0.55 to 0.42, suggesting that variations in these controls capture important information on N_2O flux variations on a global scale. Exclusion of the factor O2 (experiment 4) overpredicts N_2O production in well drained soils.

Experiment 6 considers the status of soil water and oxygen of the current month only, and results in an r^2 of 0.60. The change is mainly caused by a decrease in N2O in December for one site near Manaus, Brazil (Table 8, site 12) [Keller et al., 1986]. This and minor shifts for some other points causes a slightly improved correlation. The r^2 for the reference case and experiment 6 are similar, but since the major difference is a shift of only one point, the reference case was maintained.

4.5 *Estimate of the Global Preagricultural N_2O Emission*

A regression relationship is obtained between measured N_2O fluxes and modeled (reference case) N_2O production indices (N2O). This relationship is applied to the global distributions of monthly N_2O indices to estimate monthly fluxes. The global emission thus calculated is 6.8 Tg N_2O-N y^{-1}. The tropics (± 30° of the equator) contribute 5.4 Tg N_2O-N y^{-1} and the emission from extra-tropical regions (poleward of 30°) is 1.4 Tg N_2O-N y^{-1}.

The role of the world's wetlands in the nitrous oxide budget is uncertain. For tropical and temperate wetlands, partially represented by organic soils (group 23), the model may overestimate the potential for N_2O production. In these wetlands anaerobicity resulting from high water tables may block nitrification; this may limit denitrification rates. Furthermore, under very wet conditions, nitrous oxide can be consumed to serve as an electron acceptor. Therefore, wetlands could act as a sink for N_2O during part(s) of the year. One problem is that many wetlands mapped by Matthews and Fung [1987], ~525 × 10^6 ha globally, do not coincide with the organic soils identified in the soils data base used here. We repeated the above calculation excluding areas designated as wetlands by Matthews and Fung [1987]. In this calculation, emission and consumption of N_2O in wetlands are assumed to be equal. Wetlands cover only about 4% of the ice-free land area, and their exclusion from the analysis causes a decline in the modeled global N_2O emission of a few percent. We do not know whether N_2O emission from tropical wetlands is overestimated here, but the analysis suggests that the global contribution of wetlands to the N_2O budget is minor.

5. CONCLUSIONS

The model results show that spatial and seasonal distributions of N_2O production are very similar to climate patterns. Low winter temperatures limit N_2O production in temperate regions while in the tropics, temperature does not limit the processes involved in N_2O production. In the wet tropics, where organic matter inputs are high and both soil moisture conditions and temperatures are favorable, N_2O indices (N2O) are among the highest. This is consistent with high emissions reported for tropical forests (Table 8). While it is tempting to conclude that climate is the most important control factor, we note that C/N ratios and lignin content of the litter are not included explicitly as controls in the model. However, as their geographic variations mirror, to some extent, those of climate, we conclude that the pattern of N_2O production is determined, to first order, by the pattern of climate variation. Together with physical soil conditions, climate determines oxygen limitation and water availability. The factors FERT and O2 introduce variability among sites, without producing major impacts on the level of the N2O values.

The lack of major differences in predicted N2O between the reference case and experiment 3, in which the role of soil fertility is investigated, suggests that the model does not adequately reflect fertility levels among soils. In practice, only broad properties for soil groups are used and information to distinguish fertility differences among soil types within groups is lacking. Exclusion of the fertility index increases the variability of the N_2O potential, reflecting the simplicity of the scale.

The variability in N_2O production (expressed as the percentage of the standard deviation of the N_2O index relative to the mean within each soil group) is highest in ecosystems with overall low N2O values, i.e., in moist temperate climates, and in both temperate and tropical environments under arid and semiarid regimes. Apparently, where climate (soil water and/or temperature) is most limiting, variability in other factors results in higher percent standard deviations than those in regions with climatic conditions favorable for N_2O production; absolute standard deviations are highest in areas with high N_2O production potential.

Comparison with measurement data shows that predicted levels of N_2O production are in general agreement with measured fluxes, even though responses to long-term mean climate are compared with responses to local weather conditions prevailing during measurement periods. The ~30 flux measurements used for the comparison represent only six different ecosystems (wetlands, temperate forests, steppe, tropical savannas, tropical dry forests, and tropical rain forest). It is difficult to draw conclusions about the relative importance of various parameters on the basis of this limited data set. In addition, it is difficult to assess published measurements of nitrous oxide fluxes. In many measurement reports, site descriptions are incomplete: climate data are often absent, or provided only as annual mean precipitation and temperature; imprecise descriptions of conditions during the period of measurements are common; complete descriptions of chemical and physical soil characteristics, such as pH, texture, structure, drainage condition and soil classification, are rarely reported.

Because of the simplicity of the model and the sparcity of data, the estimate of global N_2O emission from natural ecosystems based on the regression analysis is extremely uncertain. To improve models of this type, more measurements are needed in those places expected to have high N_2O fluxes, and in regions or ecosystems which may be important contributors to the global production of N_2O due to their large area. Globally, only about 30 measurements have complete enough information to allow comparison; these do no include any data for Asia, Africa or Australia. We do not know how well the model performs in these areas with different environmental conditions and soils.

The role of soil sinks needs to be addressed in future. Consumption of N_2O has been reported [e.g., Ryden, 1981, 1983]. If this is a common phenomenon, it may have important implications for the N_2O global budget [Cicerone, 1989]. Data on consumption are too scarce to describe this process in a global model such as this one.

The 1° resolution of the soil data base does not reflect the detail of the 1:5 M soil map [FAO/Unesco, 1974-1981] used in its compilation. In digitizing the soil map, only the dominant soil type was recorded [Zobler, 1986] so that many of the associated or included soils are not represented. These minor soils may be of importance for trace gas emissions. In particular, wetlands and hydromorphic soils are poorly represented because they occur frequently as linear and scattered features that do not dominate at the 1° resolution. Even at the 1:5M scale of the FAO/Unesco soil map, they are under-represented [Van Diepen, 1985]. Parallel to the need for greater spatial resolution is the need for greater information resolution about soil fertility, drainage, and texture. In the model, only five levels of these properties are resolved, although there are >100 soil types. To improve the model, soil data bases including a number of soil characteristics vital to evaluating fertility are required. More spatial and temporal detail in data bases of vegetation (NPP) and litter composition would allow a better description of the temporal and geographic variability of controls on N_2O fluxes and, possibly, episodic pulses of N_2O.

The latitudinal and seasonal distributions of N_2O fluxes modeled here may be used as inputs to two- and three-dimensional models of the atmosphere to test hypotheses about the N_2O budget.

APPENDIX A

The primary gridded data sets used in the model, commented upon briefly in the text, are discussed more fully below.

A.1. *Climate*

Shea [1986] produced climatologies of monthly surface air temperature and precipitation, at 2.5° resolution for the globe, from station observations. Lacking a global climatology for soil temperatures, we used surface air temperatures. This may introduce phase errors, of up to a season in middle and high latitudes, in the seasonality of N_2O production.

A.2. *Soil Type, Texture, Fertility, and Drainage*

The global distribution of soil properties was obtained from the data base of Zobler [1986], compiled in digital form at 1° resolution from the FAO/Unesco [1974-1981] Soil Map of the World. The 1:5M FAO/Unesco soil maps distinguish dominant soil units, associated soils and inclusions, topsoil texture of the dominant soil and slope. On the maps, additional information on phases is indicated with special symbols. The full digital data base of Zobler [1986] includes distributions of major and associated soil units, soil texture, slope, and phase. The data sets used in this study are major soil units and soil texture.

The FAO/Unesco [1974-1981] soil classification system has two levels: soil groups and soil units. There are 26 soil groups encompassing 106 soil units. The soil groups and soil units are classified on the basis of diagnostic horizons and diagnostic properties. Descriptions of the soil groups and soil units can be found in the works by FAO/Unesco [1974-1981], Fitzpatrick [1983] and Driessen and Dudal [1991]. Two of the soil units, gelic Planosols, and ferric Podzols, do not occur in the digital data base because they never dominate at 1° resolution.

For this study, soil units are aggregated into 23 new groups. Table 1 lists the 23 groups and their areas, presented under 10 higher-level soil clusters (I-X). The global distribution of the 23 new groups is shown in Plate 1. Soils are formed through the impact of climate, vegetation, fauna (including humans) and topography on the parent material. The relative influence of these soil-forming factors varies among sites, explaining the considerable variety found in soils. Globally, climate is the major soil-forming factor and under similar climatic conditions, soil development is sufficiently consistent to form a basis for soil classification. Such zonal soils are represented in Table 1 by clusters II-IV and VI-VII. Variations occur where parent rock (clusters VIII and X), physiographic position (IX) or other local features dominate soil formation. These soils are intrazonal and azonal soils with no clear relation to vegetation and climate.

In this model, individual gelic soil types are combined to form the permafrost soil cluster. In addition, several soils are combined following the new terminology of FAO/Unesco [1988]: all shallow soils (Lithosols, Rankers, and Rendzinas) are grouped as Leptosols (group 21), and weakly-developed soils under arid and semiarid moisture regimes, Xerosols and Yermosols, are grouped as desert soils (group 14).

The data base of soil units provides the basis for deriving information on two factors in the model: fertility and drainage. Indices for these factors, ranging from one to five, are associated with each of the 106 soil units as shown in Table 1 and discussed in section 3.

The reliability of the FAO/Unesco soil map is not spatially uniform. Reliability is particularly low in the Amazon basin, the former Soviet Union, parts of eastern Africa, and Europe. Additional information has become available since compilation of the FAO/Unesco soil maps in the 1960s, reflected in the revised legend of FAO/Unesco [1988].

Topsoil texture is defined as the relative proportions of clay (particles < 2 μm), silt (2-50 μm), and sand (50-2000 μm) in the top 30 cm of the soil. The FAO/Unesco soil maps have three broad texture classes for the topsoil: coarse, medium, and fine. In addition to these texture classes, the digital data set identifies several texture combinations; the organic class is for nonmineral topsoils (Table 2). Topsoils with coarse textures have <18% clay and >65% sand and include sands, loamy sands and sandy loams. The medium texture class, with <35% clay and <65% sand, includes sandy loams, loams, sandy clay loams, silt loams, silt s, silty clay loams, and clay loams. Fine-textured topsoils have >35% clay and include clays, silty clays, sandy clays, clay loams, and silty clay loams. The reader is referred to the texture triangle in FAO/Unesco [1974-1981] and to U.S. Department of Agiculture [1975] for further information on characteristics of texture classes.

A.3. *Vegetation*

The satellite-derived normalized difference vegetation index (NDVI) is a measure of the primary productivity of vegetation [Box et al., 1989]. The NDVI is calculated as the difference between radiances in the visible (0.58-0.68 μm) and near infrared (0.725-1.1 μm) portions of the spectrum normalized by the sum of the radiances. The Advanced Very High Resolution Radiometer (AVHRR) on board the NOAA series of polar-orbiting satellites [Tarpley et al., 1984] routinely measures the radiances. The weekly maximum NDVI's at ~25 km resolution obtained from NOAA for 1984 were further sampled and averaged for this study. First, the maximum monthly NDVI at 25 km

resolution was retained from the weekly maxima. These dates were then averaged to 1° resolution. The digital data base of vegetation types compiled by Matthews [1983] is used for verifying measurement site characteristics and for analysis of model results.

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